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# SPECTRA IN THE 70 Å - 345 Å WAVELENGTH REGION OF ELEMENTS INJECTED INTO THE PLT TOKAMAK*

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ABSTRACT

High resolution spectra of the elements Fe, Ni, Zn, Ge, Se, and Mo injected into the PLT tokamak have been recorded by the 2 meter Schwob-Fraenkel soft x-ray multichannel spectrometer (SOXMOS). Spectra were recorded every 50 ms during the time before and after injection. The spectral lines of the injected element were very strong in the spectrum recorded immediately after injection, and the transitions in the injected element were easily distinguished from the transitions in the intrinsic elements (mostly Fe, Ti, and Cr). An accurate wavelength scale was established using well-known reference transitions in the intrinsic elements. The spectra recorded just prior to injection were subtracted from the spectra recorded after injection, and the resulting spectrum is composed almost entirely of transitions from the injected element. A large number of $\Delta n=0$ transitions in the Li I through K I (except Ne I) isoelectronic sequences of the injected elements were identified in the wavelength region 70 Å to 345 Å.



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## INTRODUCTION

The PLT tokamak represents a very useful tool for the study of the spectra of highly-charged ions. Electron temperatures of up to 2.5 keV occur in the center of the Ohmically heated discharge and persist for a time period of up to 1 sec. Since this time period is typically long compared to the ionization and recombination times of the highly-charged ions from the wall material, the spectra of these ions are essentially steady during most of the plateau regime of the discharge. The spectra of transiently injected elements are easily detected against the steady background spectra of the intrinsic elements.

Time resolved spectra of the intrinsic elements (C, O, Ti, Cr, Fe, and Ni) and of injected elements have been recorded using the 2 meter Schwob-Fraenkel soft x-ray multichannel spectrometer (SOXMOS). Spectra were recorded every 50 ms in the 70 Å - 345 Å wavelength region. Corrections were made for nonlinearities in the multichannel detector and the fiber optic transmission line, and an accurate wavelength scale was established using well-known reference lines. A number of spectra were added together to improve the signal-to-noise ratio. The experimental technique and the spectra from the intrinsic elements were presented in Ref. 1. In the present paper, we present the spectra of the injected elements Fe, Ni, Zn, Ge, Se, and Mo.

## DATA ANALYSIS

The spectra of the injected elements were recorded by the SOXMOS spectrometer[2-4] fitted with a 600 $\ell$/mm grating and a blaze angle of 1° 31'. The spectra were detected by a flat $MgF_2$-coated microchannel plate (MCP) that was coupled to a 1024 pixel photodiode array by a fiber optic transmission line. On each discharge, data in a 50 Å wide wavelength interval could be recorded, and the wavelength region from 70 Å to 345 Å was covered by moving the MCP. Spectral scans were recorded every 50 ms throughout the discharge, and typically 10 usable scans with strong spectral features were obtained on each discharge. Wavelength corrections were made to account for the nonlinearities in the fiber optic taper and in the pixel positions, and a wavelength scale accurate to 0.01 Å was established. At fixed times measured from the beginning of the discharges, the 50 Å wide spectra were connected together to produce a composite spectrum covering the 70 Å - 345 Å wavelength range. The details of the data reduction were given in Ref. 1.

The elements were injected during the plateau regime of Ohmically heated discharges using the laser blowoff technique. Before the time of injection, the recorded spectra are composed of transitions in highly-charged ions of the elements from the wall material (mostly Fe, Ti, and Cr). We shall refer to this spectrum as the background spectrum. At the time of injection, strong spectral features from the injected element appear superimposed on the background spectrum, and these spectral features diminish in the scans following injection. The background spectrum after injection is similar to the background spectrum before injection, and this implies that the injection is a rather minor

perturbation on the plasma. By subtracting the spectrum recorded just before injection from the spectrum recorded after injection, a resulting spectrum is obtained that is composed almost entirely of transitions in the highly-charged ions of the injected elements.

The spectra of the injected elements Fe, Ni, Zn, Ge, Se, and Mo are presented in Figs. 1-6. These spectra are the result of subtracting the scans recorded just before injection from the scans recorded after injection. Nearly all of the emission features are the result of transitions in the injected element that increase dramatically during injection and appear quite strong in the subtracted spectra. A few of the emission features are the result of particularly strong lines of the background elements Fe, Ti, Cr, and Ni that are increasing during the time of injection. These lines appear in the subtracted spectra as weak emission features and are indicated by the label BKG. Many of the dips in the subtracted spectra are the result of background lines that are decreasing during injection.

The identification of the spectral lines is based on previous experimental measurements[5-23] or on the recommendations of Edlen[24-28]. All of the strong lines in the injected spectra of Fe, Ni, and Zn have been identified. Most of the strong lines in the Ge, Se, and Mo spectra have been identified, but several features remain unidentified. Transitions in the isoelectronic sequences Li I through K I (except Ne I) have been identified. With the exception of several Na I transitions, all of these transitions are of the type $\Delta n=0$ and terminate on

levels within the ground configurations of the ions. The present identifications are summarized in Table I, and the presently measured and the previous wavelengths are also listed. The estimated accuracy of our measured wavelengths is 0.02 Å.

## CONCLUSIONS

We have presented survey spectra of the elements Fe, Ni, Zn, Ge, Se, and Mo that were injected into the PLT tokamak plasma. An accurate wavelength scale was established, and the wavelengths were measured to an accuracy of 0.02 Å. A number of new transitions in Ge, Se, and Mo were identified.

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## FIGURE CAPTIONS

Fig. 1 PLT spectrum of injected iron.

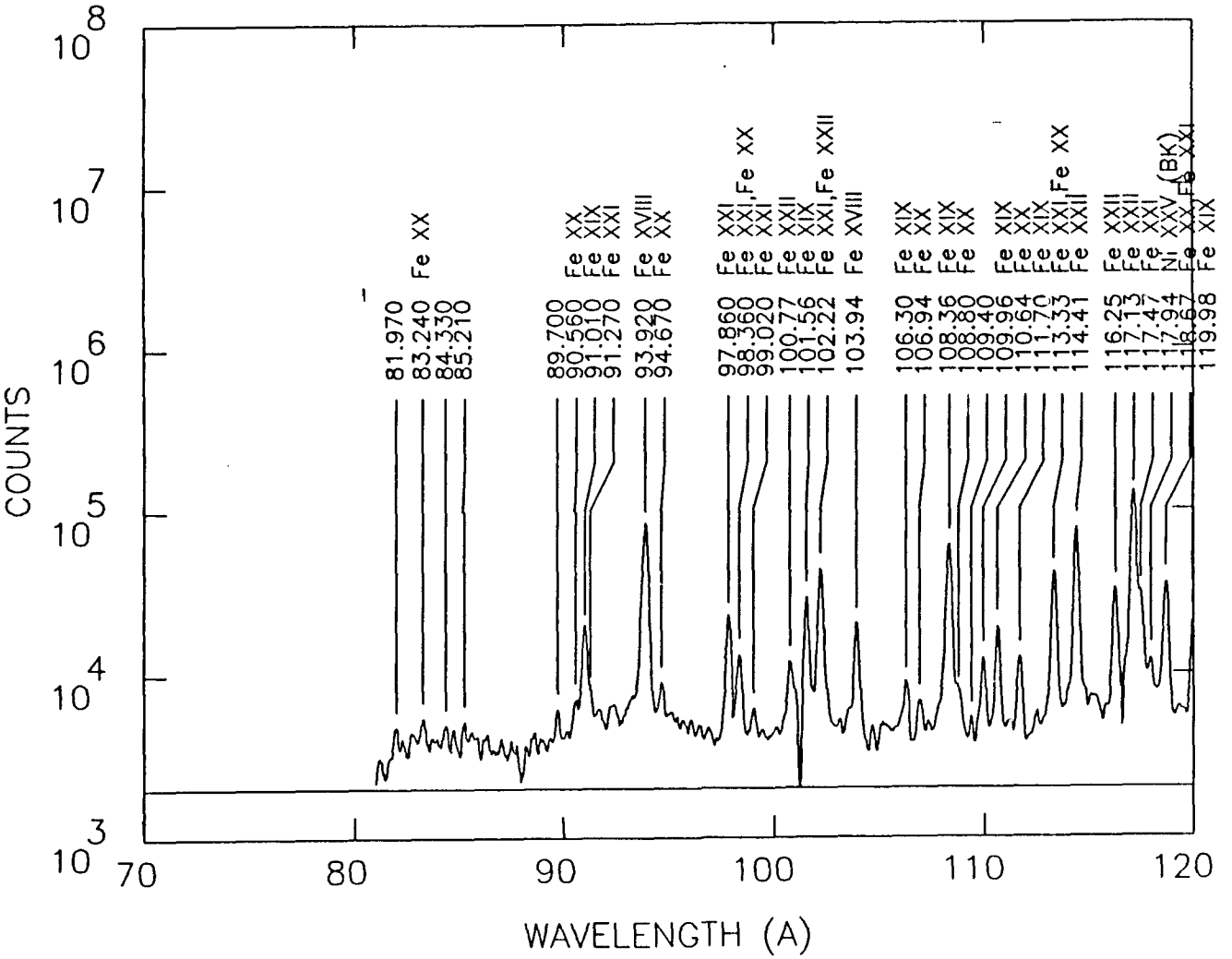
Fig. 2 PLT spectrum of injected nickel.

Fig. 3 PLT spectrum of injected zinc.

Fig. 4 PLT spectrum of injected germanium.

Fig. 5 PLT spectrum of injected selenium.

Fig. 6 PLT spectrum of injected molybdenum.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84.330
85.210
89.700 Fe XX
90.560 Fe XIX
91.010 Fe XXI
91.270
93.920 Fe XVIII
94.670 Fe XX
97.860 Fe XXI
98.360 Fe XXI,Fe XX
99.020 Fe XXII
100.77 Fe XIX
101.56 Fe XXI,Fe XXII
102.22
103.94 Fe XVIII
106.30 Fe XIX
106.94 Fe XX
108.36 Fe XIX
108.80 Fe XX
109.40 Fe XIX
109.96 Fe XX
110.64 Fe XIX
111.70 Fe XXI,Fe XX
113.33 Fe XXII
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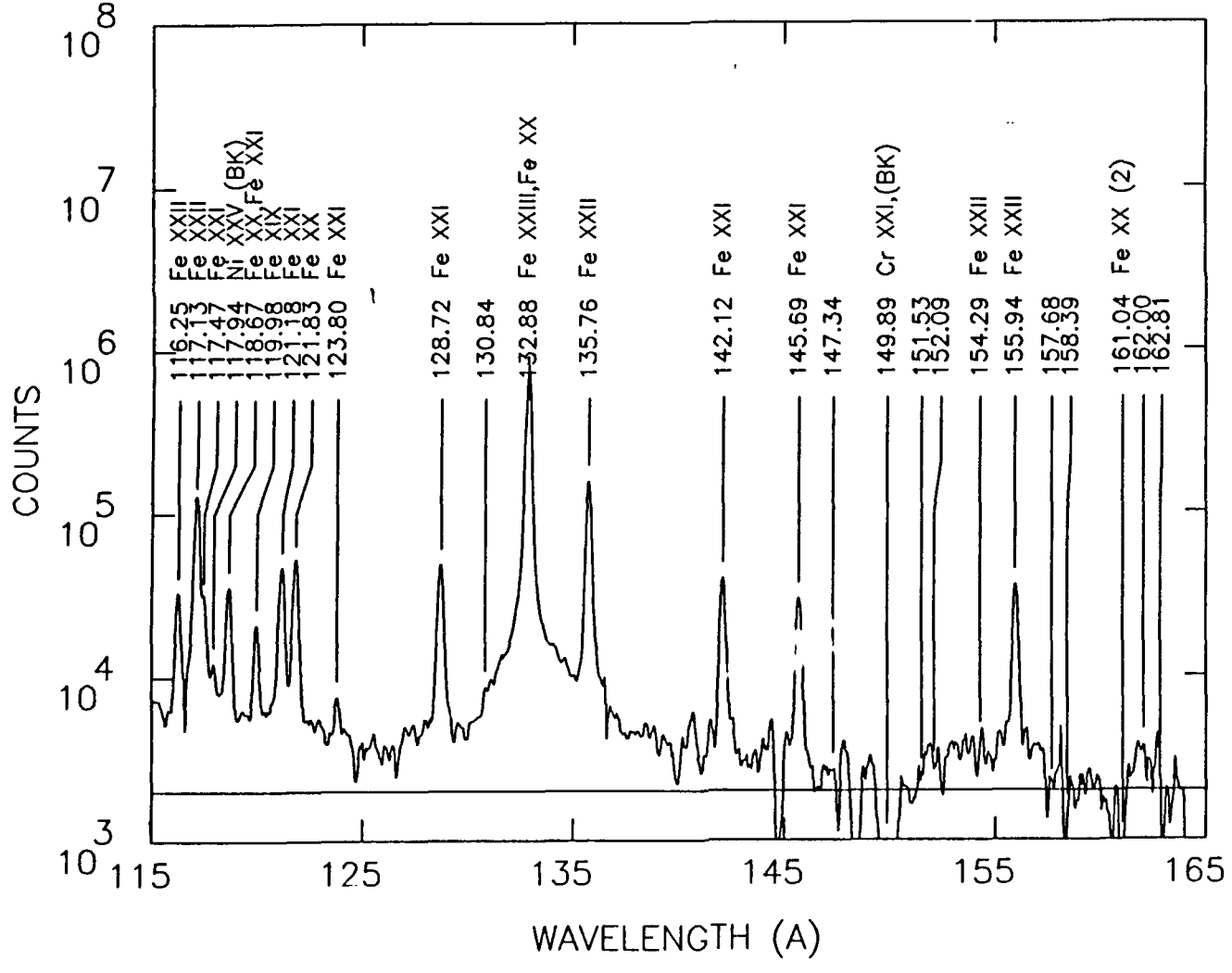
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118.67 Fe XX,Fe XXI
119.98 Fe XIX
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121.83 Fe XX
123.80 Fe XXI
128.72 Fe XXI
130.84
132.88 Fe XXIII,Fe XX
135.76 Fe XXII
142.12 Fe XXI
145.69 Fe XXI
147.34
149.89 Cr XXI,(BK)
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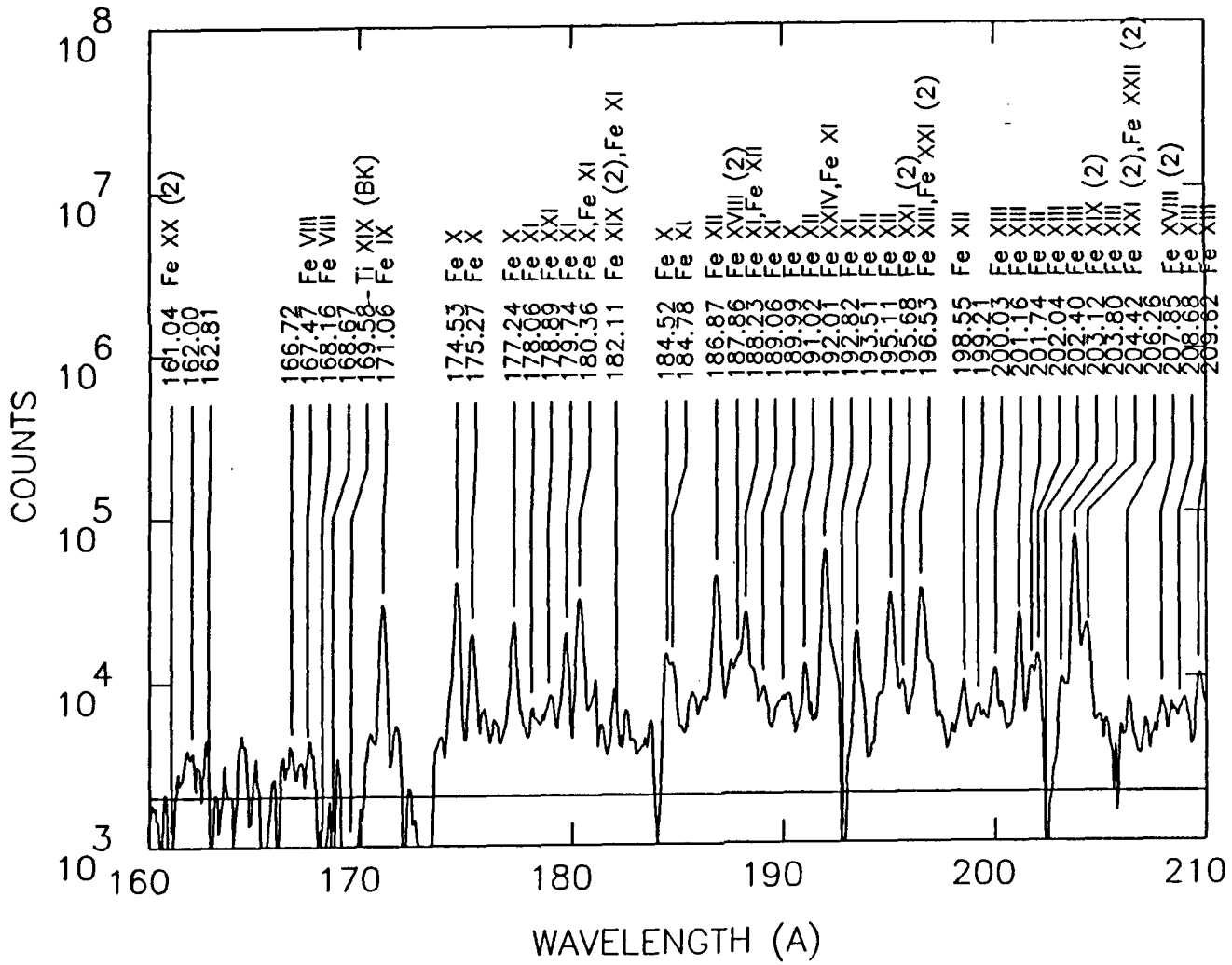
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190
200
210
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Fe VIII
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Fe IX
Fe X
Fe X
Fe X
Fe XI
Fe XXI
Fe X,Fe XI
Fe XIX (2),Fe XI
Fe X
Fe XI
Fe XII
Fe XVIII (2)
Fe XI,Fe XII
Fe XI
Fe X
Fe XII
Fe XXIV,Fe XI
Fe XI
Fe XII
Fe XII
Fe XXI (2)
Fe XIII,Fe XXI (2)
Fe XII
Fe XIII
Fe XIII
Fe XIII
Fe XIII
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Fe XIII
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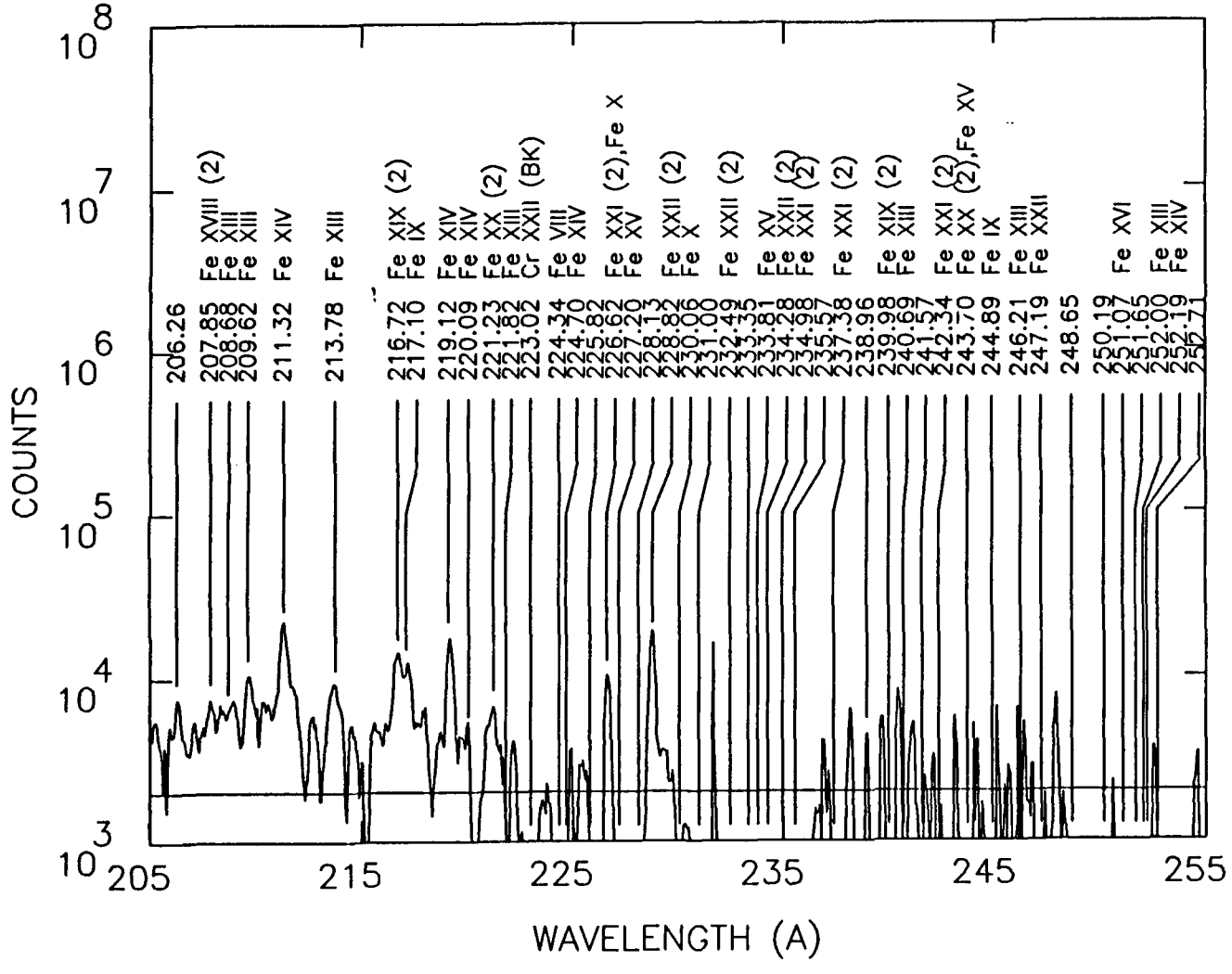
Fe XIII
Fe XIII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215
225
235
245
255
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208.68 Fe XIII
209.62 Fe XIII
211.32 Fe XIV
213.78 Fe XIII
216.72 Fe XIX (2)
217.10 Fe IX
219.12 Fe XIV
220.09 Fe XIV
221.23 Fe XX (2)
221.82 Fe XIII
223.02 Cr XXII (BK)
224.34 Fe VIII
224.70 Fe XIV
225.82
226.62 Fe XXI (2),Fe X
227.20 Fe XV
228.13
228.82 Fe XXII (2)
230.06 Fe X
231.00
232.49 Fe XXII (2)
233.35
233.81 Fe XV
234.28 Fe XXII (2)
234.98 Fe XXI (2)
235.57
237.38 Fe XXI (2)
238.96
239.98 Fe XIX (2)
240.69 Fe XIII
241.57
242.34 Fe XXI (2)
243.10 Fe XX (2),Fe XV
244.89 Fe IX
246.21 Fe XIII
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250.19
251.07 Fe XVI
251.65
252.00 Fe XIII
252.19 Fe XIV
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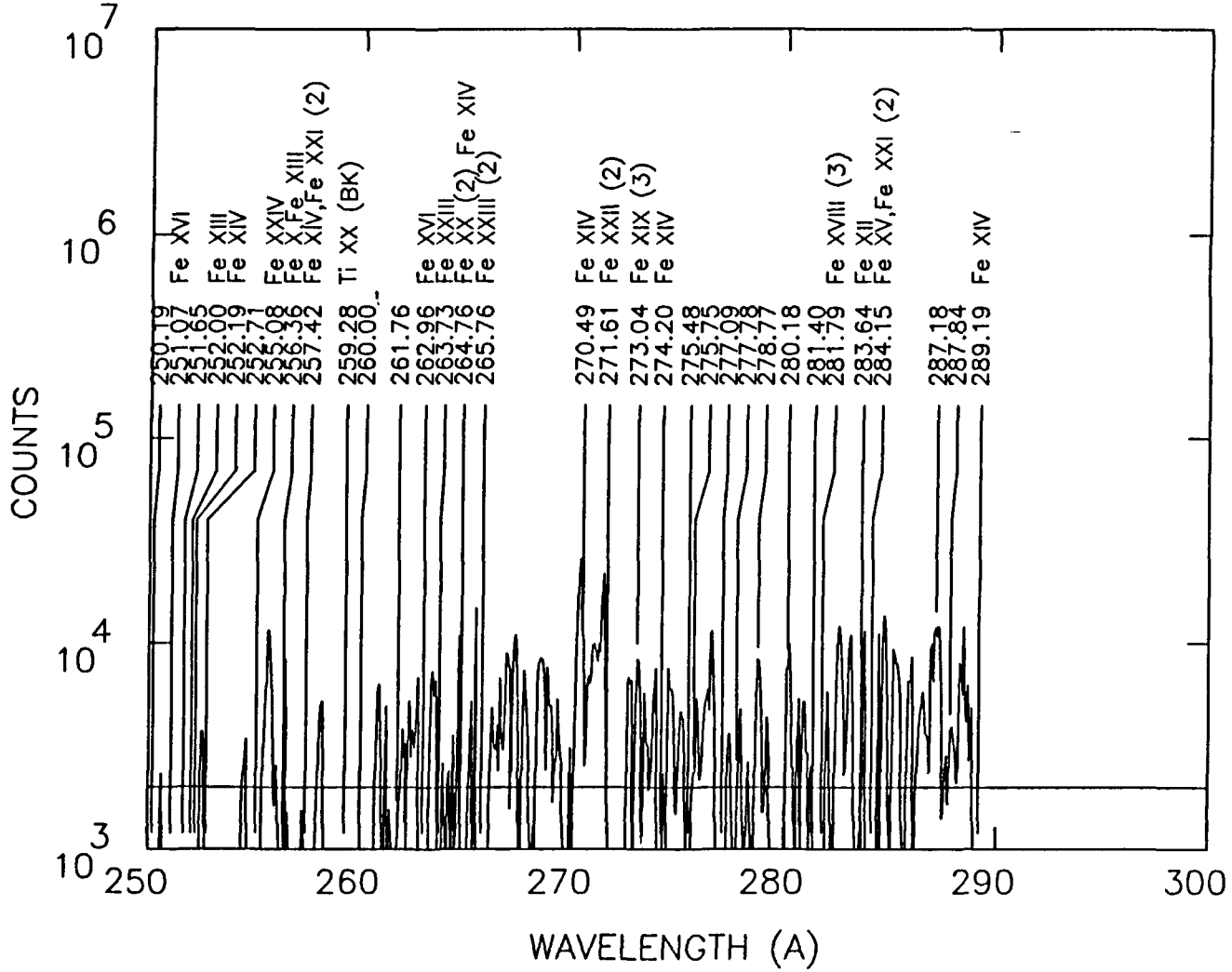
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252.19
252.71
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256.36 Fe X,Fe XIII
257.42 Fe XIV,Fe XXI (2)
259.28 Ti XX (BK)
260.00
261.76
262.96 Fe XVI
263.73 Fe XXIII
264.76 Fe XX (2),Fe XIV
265.76 Fe XXIII (2)
270.49 Fe XIV
271.61 Fe XXII (2)
273.04 Fe XIX (3)
274.20 Fe XIV
275.48
275.75
277.09
277.78
278.77
280.18
281.40 Fe XVIII (3)
281.79
283.64 Fe XII
284.15 Fe XV,Fe XXI (2)
287.18
287.84
289.19 Fe XIV

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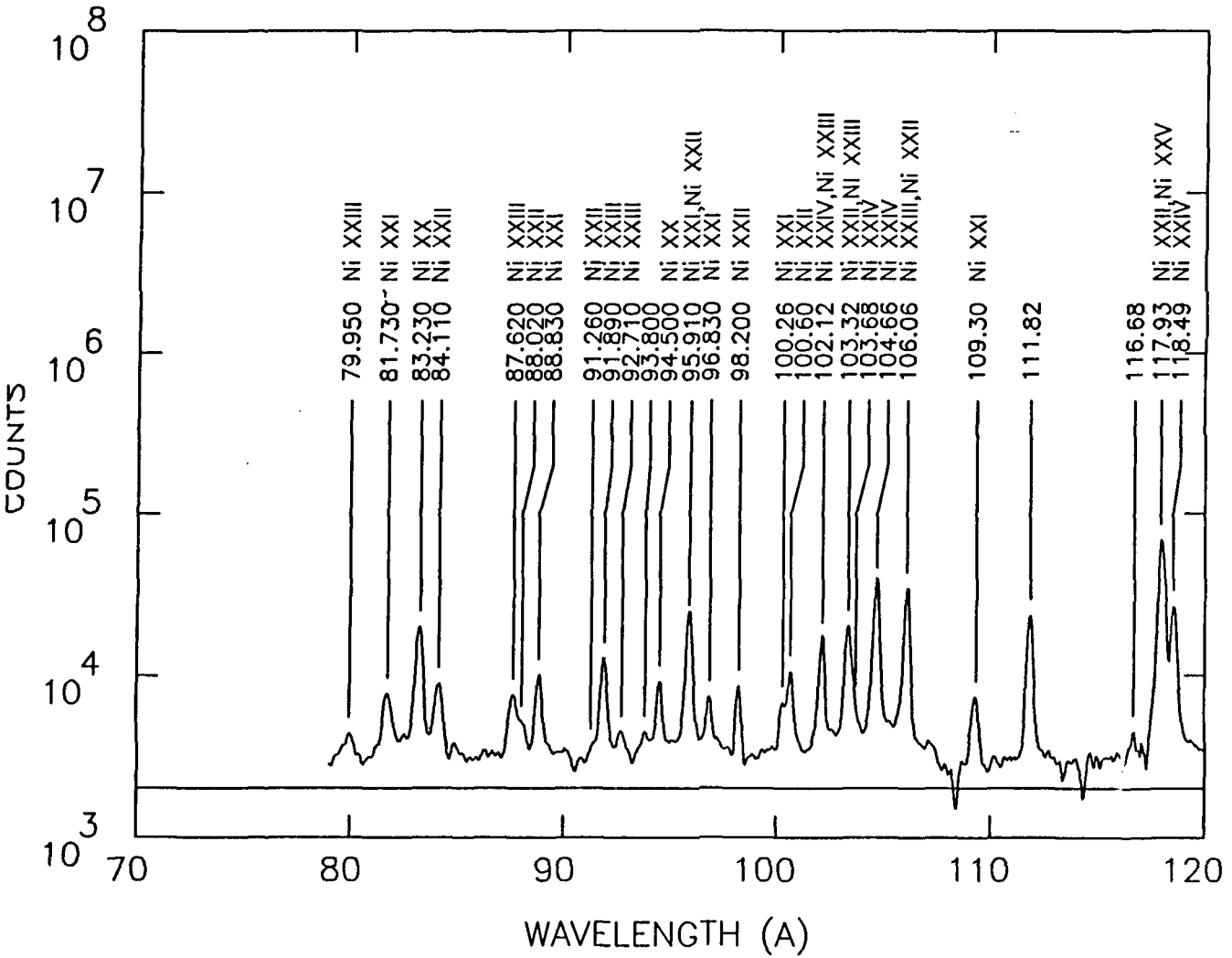
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91.890 Ni XXIII
92.710 Ni XXIII
93.800 Ni XX
94.500 Ni XXI,Ni XXII
95.910 Ni XXI
96.830 Ni XXII
98.200 Ni XXII
100.26 Ni XXI
100.60 Ni XXII
102.12 Ni XXIV,Ni XXIII
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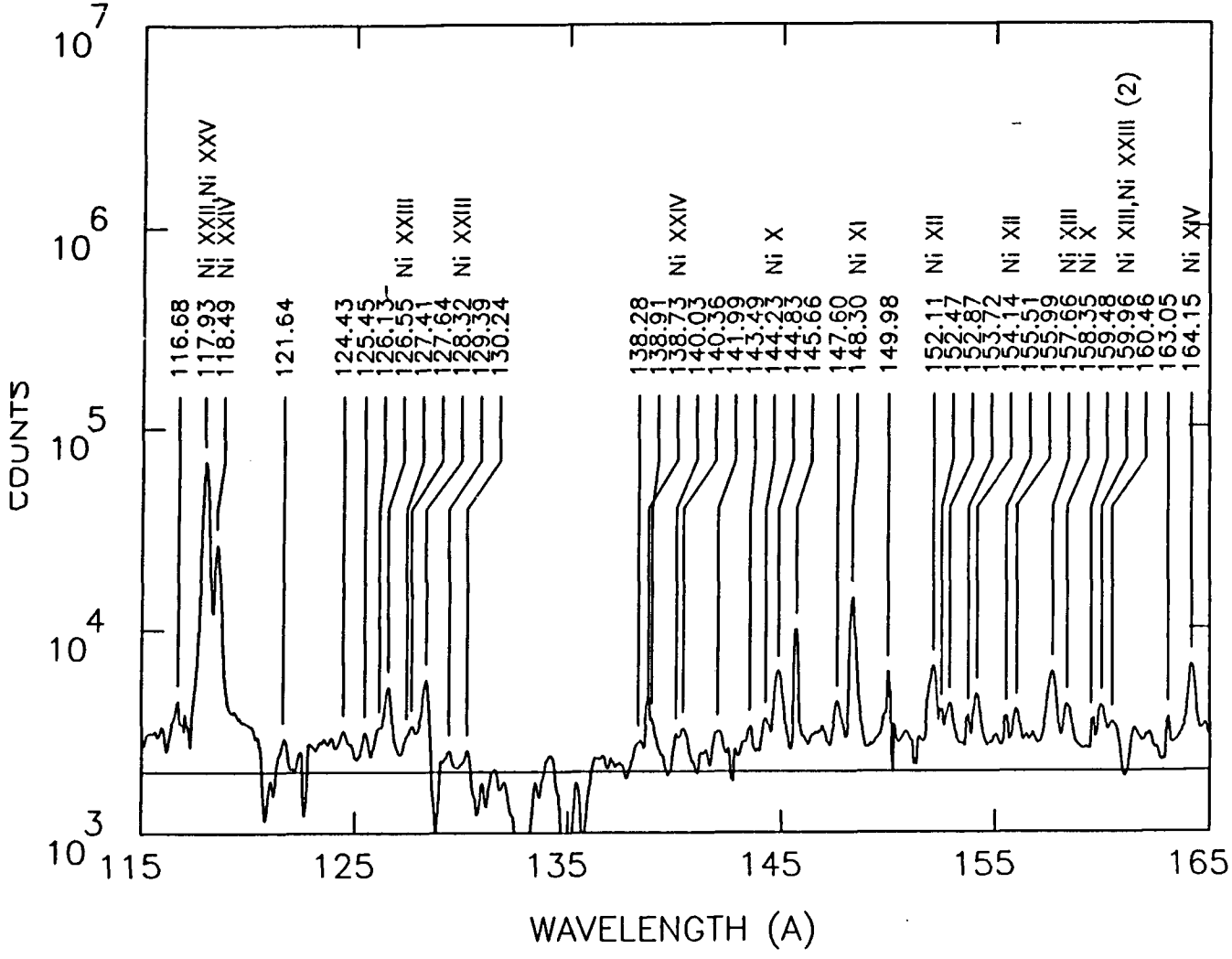
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127.41
127.64
128.32
129.39
130.24
Ni XXIII
Ni XXIII
138.28
138.91
138.73
140.03
140.36
141.99
143.49
144.23
144.83
145.66
147.60
148.30
149.98
Ni XXIV
Ni X
Ni XI
152.11
152.47
152.87
153.72
154.14
155.51
155.99
157.66
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Ni XIII
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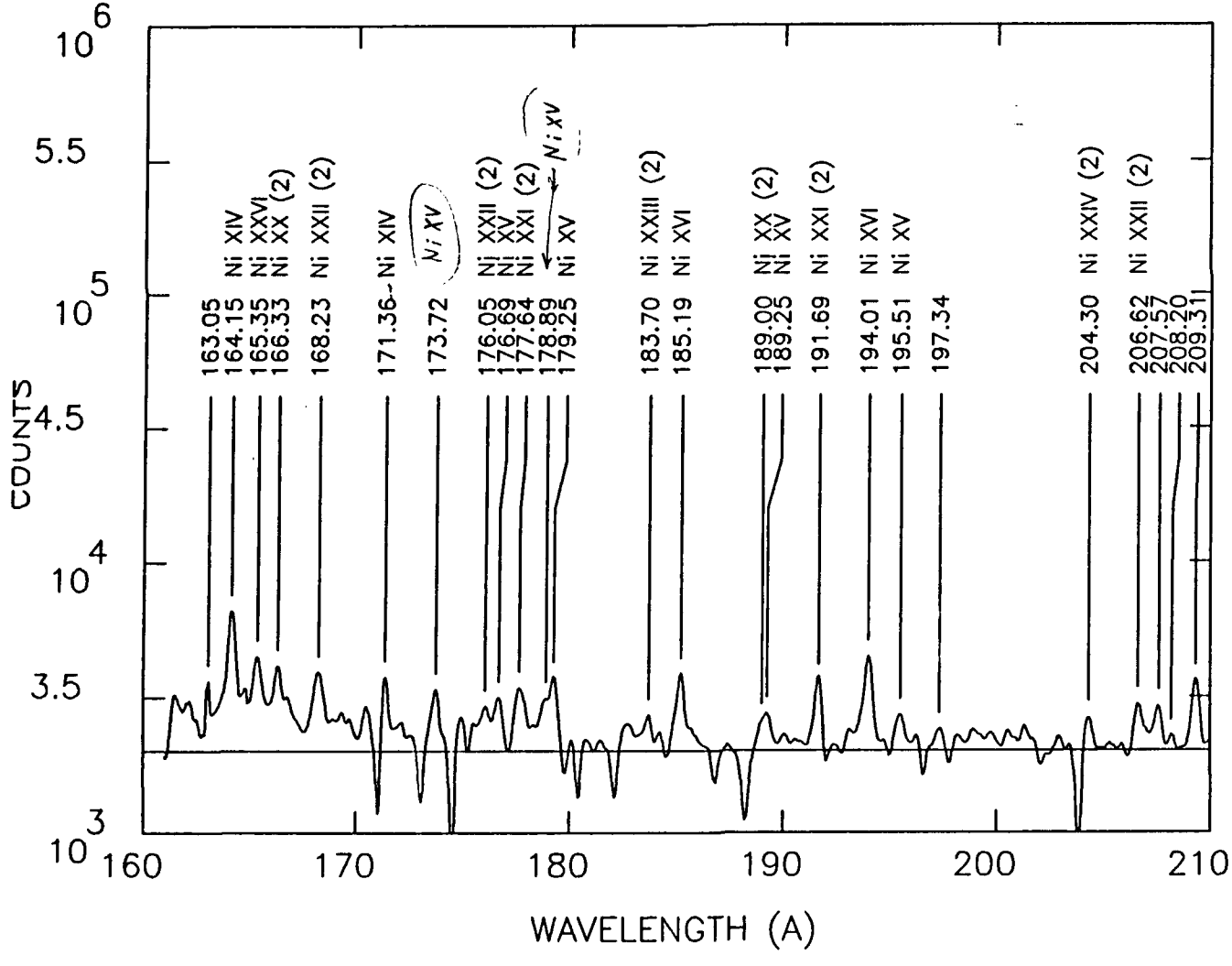
Ni XIV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189.25 Ni XV
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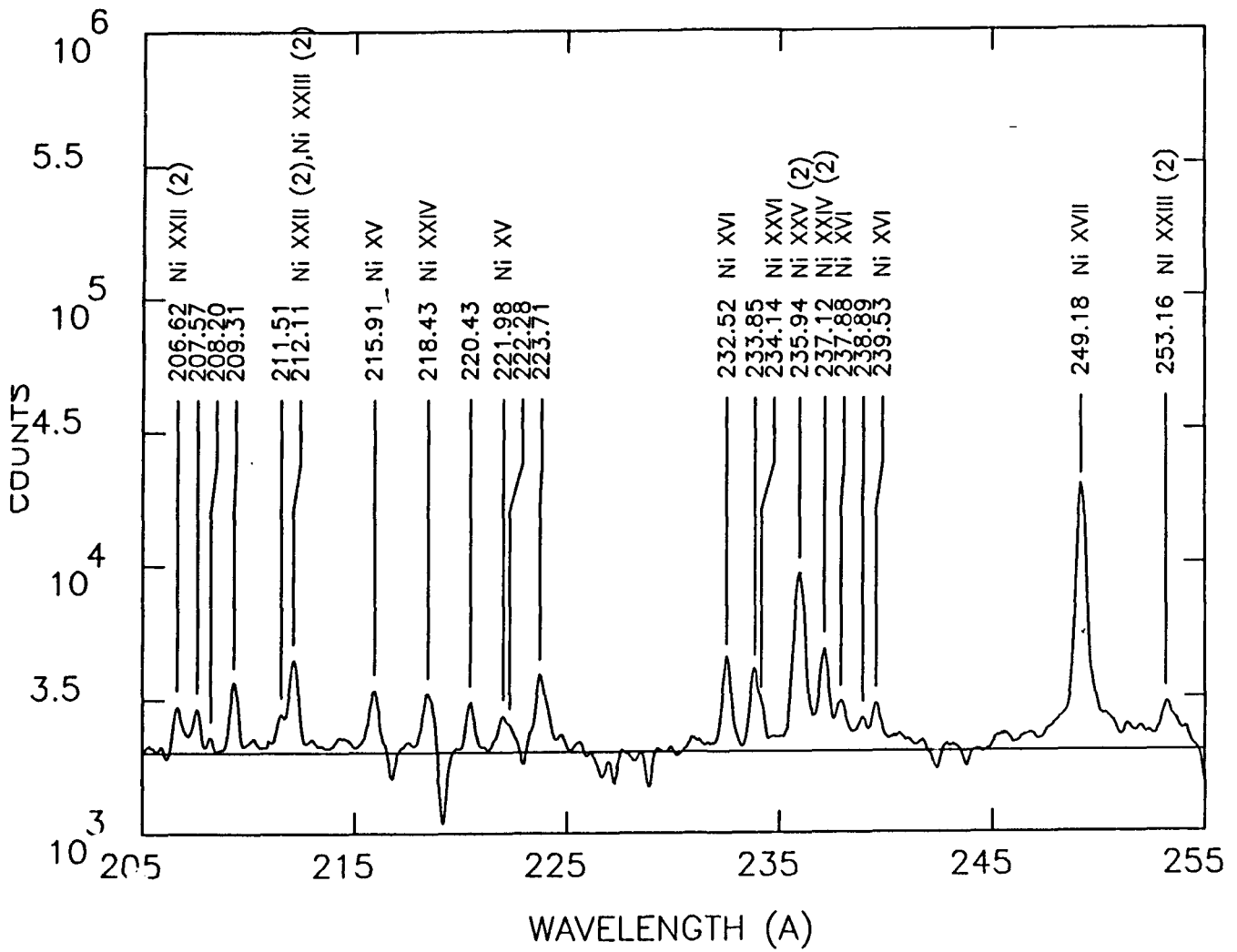
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Ni XV
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Ni XV
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223.71
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Ni XXIV (2)
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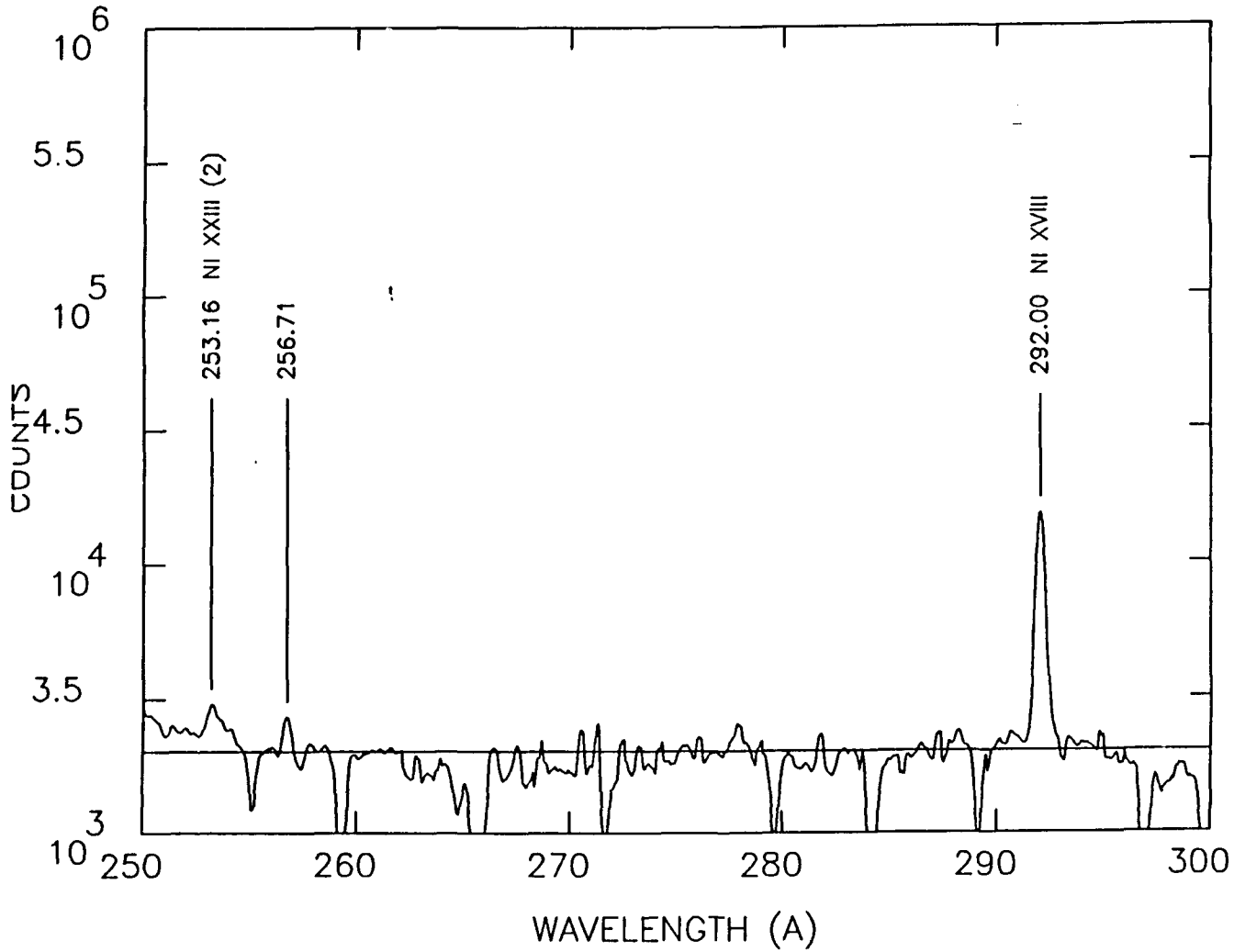
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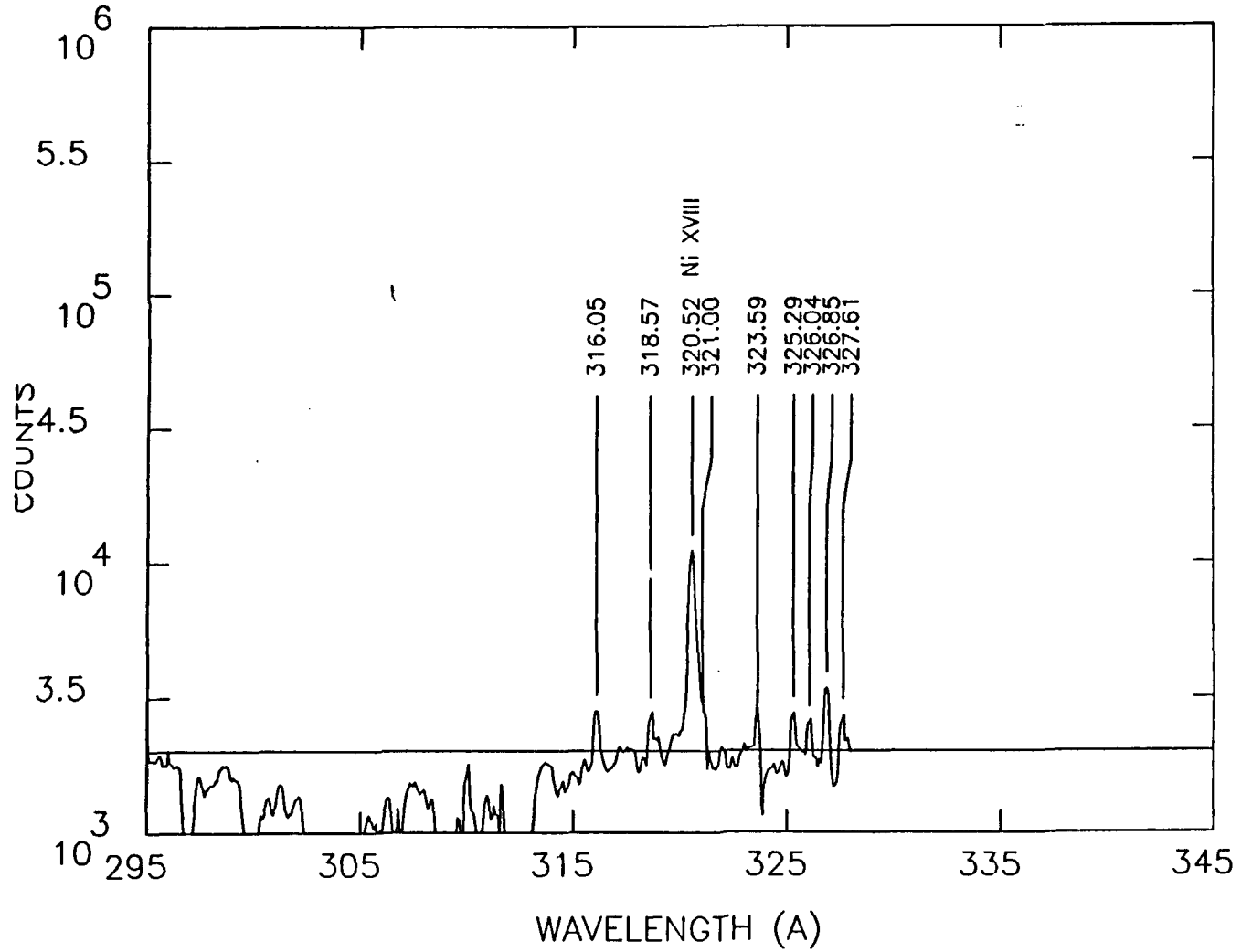
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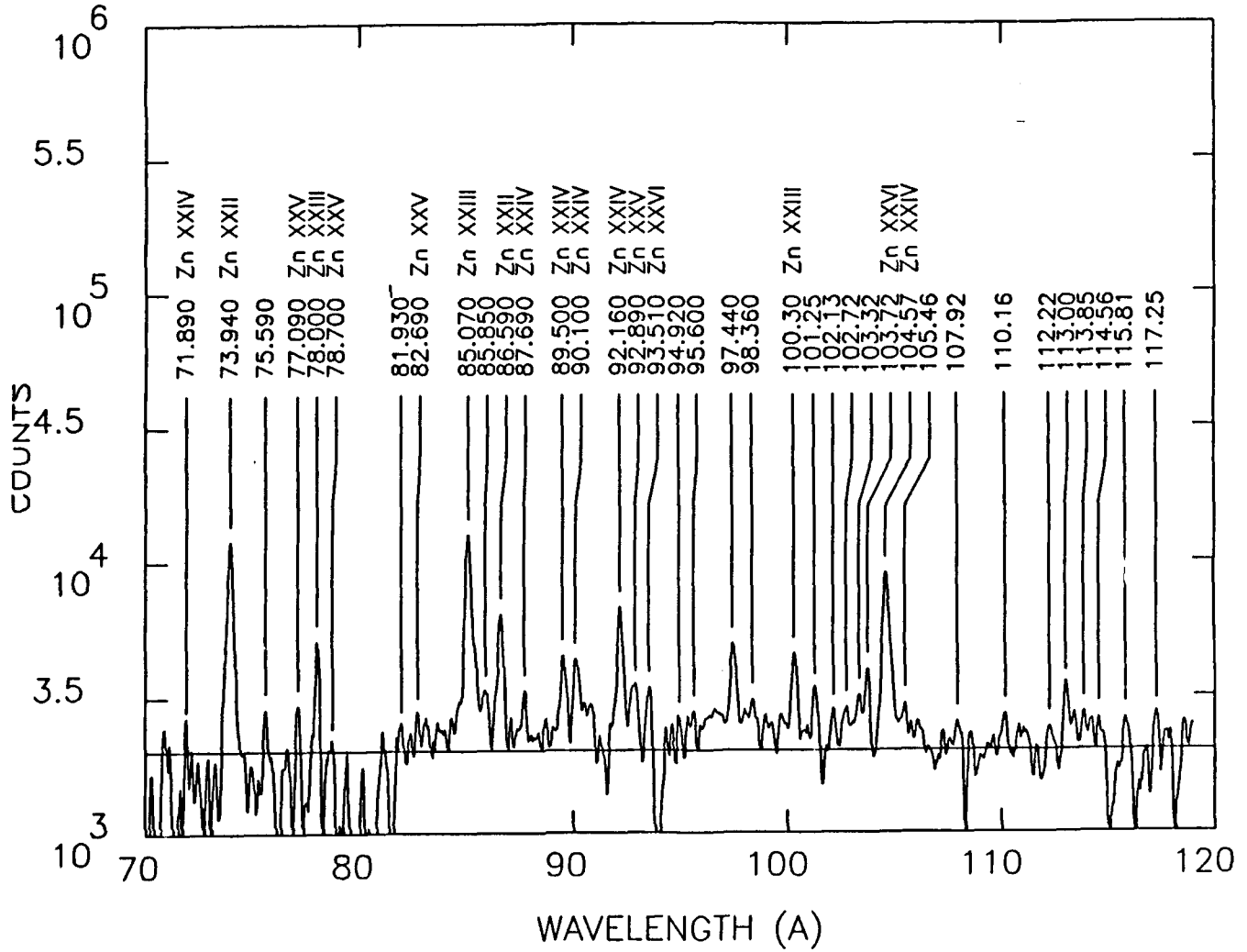
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100
110
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73.940 Zn XXII
75.590
77.090 Zn XXV
78.000 Zn XXIII
78.700 Zn XXV
81.930
82.690 Zn XXV
85.070 Zn XXIII
85.850
86.590 Zn XXII
87.690 Zn XXIV
89.500 Zn XXIV
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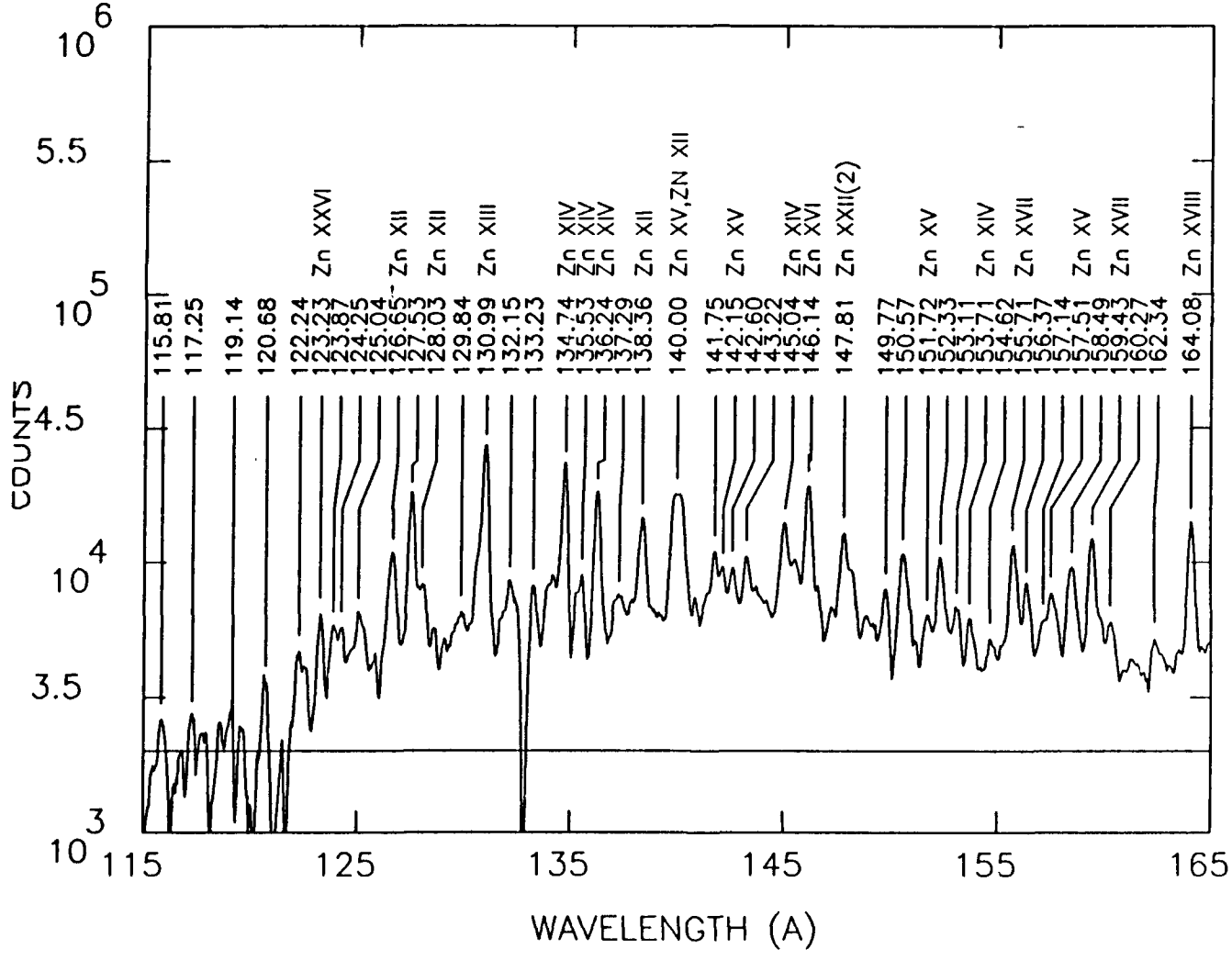
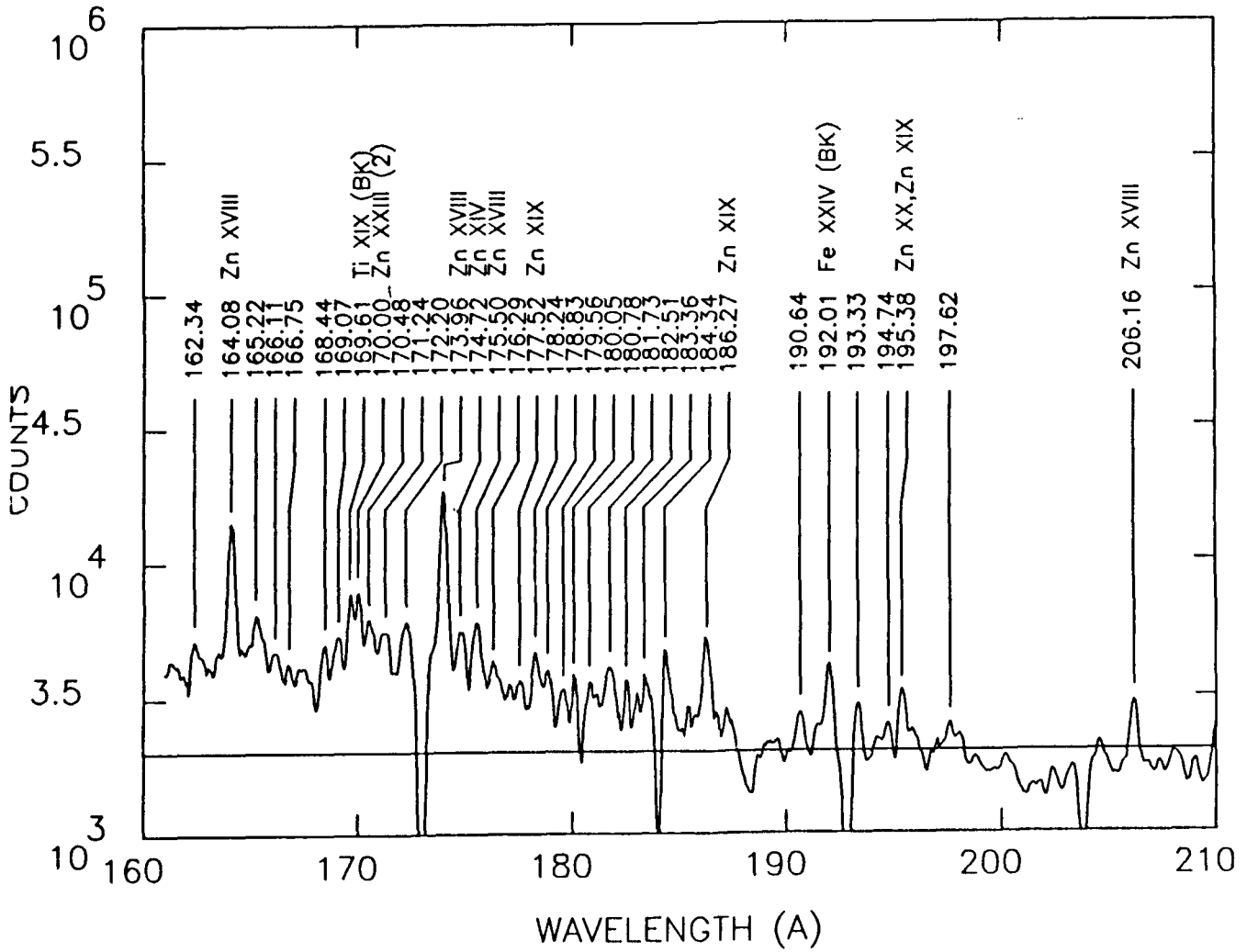
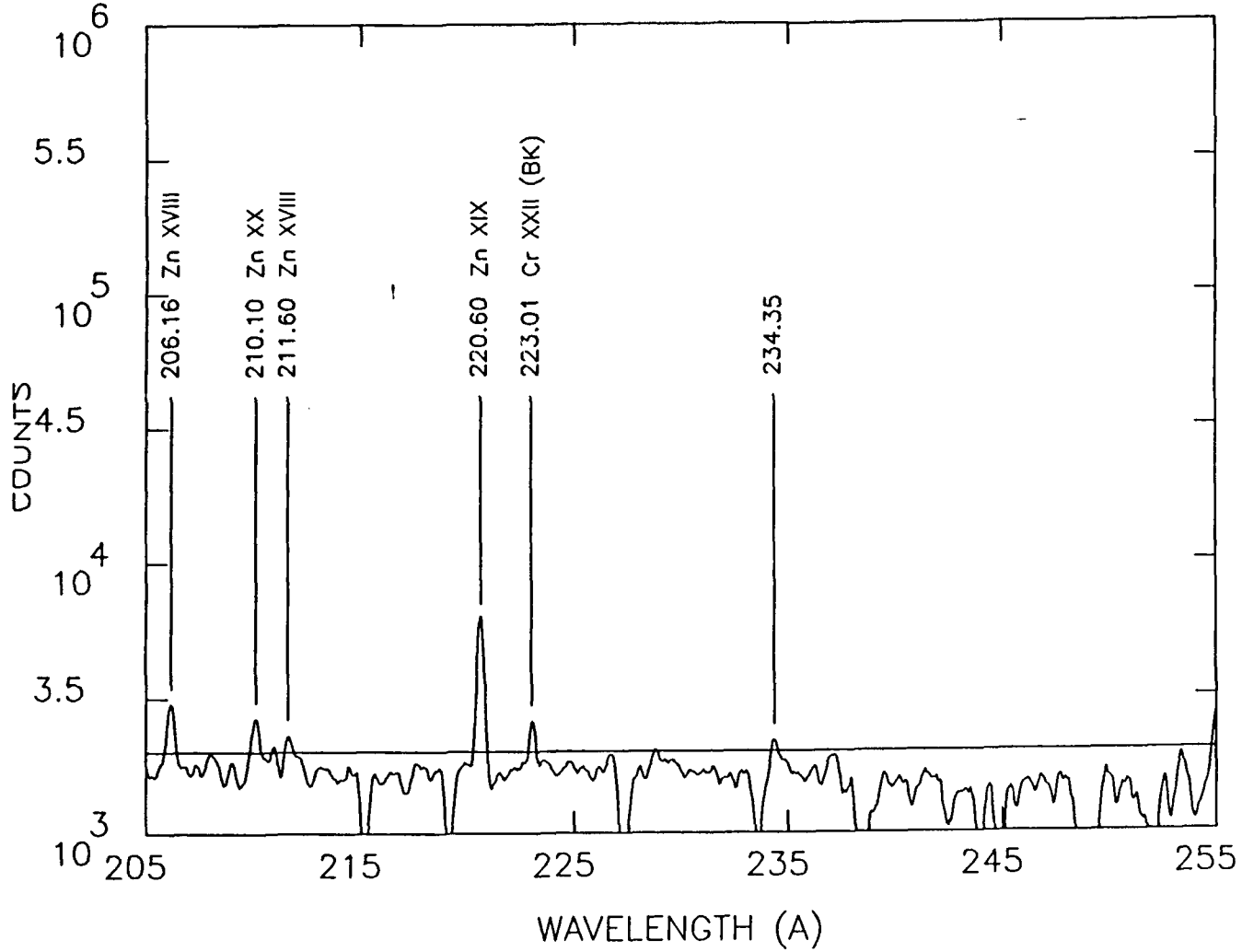
117.25


COUNTS
WAVELENGTH (A)
115.81
117.25
119.14
120.68
122.24 Zn XXVI
123.23
123.87
124.25
126.04
126.65 Zn XII
127.53
128.03 Zn XII
129.84
130.99 Zn XIII
132.15
133.23
134.74 Zn XIV
135.53 Zn XIV
136.24 Zn XIV
137.29
138.36 Zn XII
140.00 Zn XV,ZN XII
141.75
142.15 Zn XV
142.60
143.22
145.04 Zn XIV
146.14 Zn XVI
147.81 Zn XXII(2)
149.77
150.57
151.72 Zn XV
152.33
153.11
153.71 Zn XIV
154.62 Zn XVII
155.71
156.37
157.14
157.51 Zn XV
158.49
159.43 Zn XVII
160.27
162.34
164.08 Zn XVIII


COUNTS
WAVELENGTH (A)
162.34
164.08 Zn XVIII
165.22
166.11
166.75
168.44
169.07
169.61 Ti XIX (BK)
170.00 Zn XXIII (2)
170.48
171.24
172.20
173.96 Zn XVIII
174.72 Zn XIV
175.50 Zn XVIII
176.29
177.52 Zn XIX
178.24
178.83
179.56
180.05
180.78
181.73
182.51
183.36
184.34
186.27 Zn XIX
190.64
192.01 Fe XXIV (BK)
193.33
194.74
195.38 Zn XX,Zn XIX
197.62
206.16 Zn XVIII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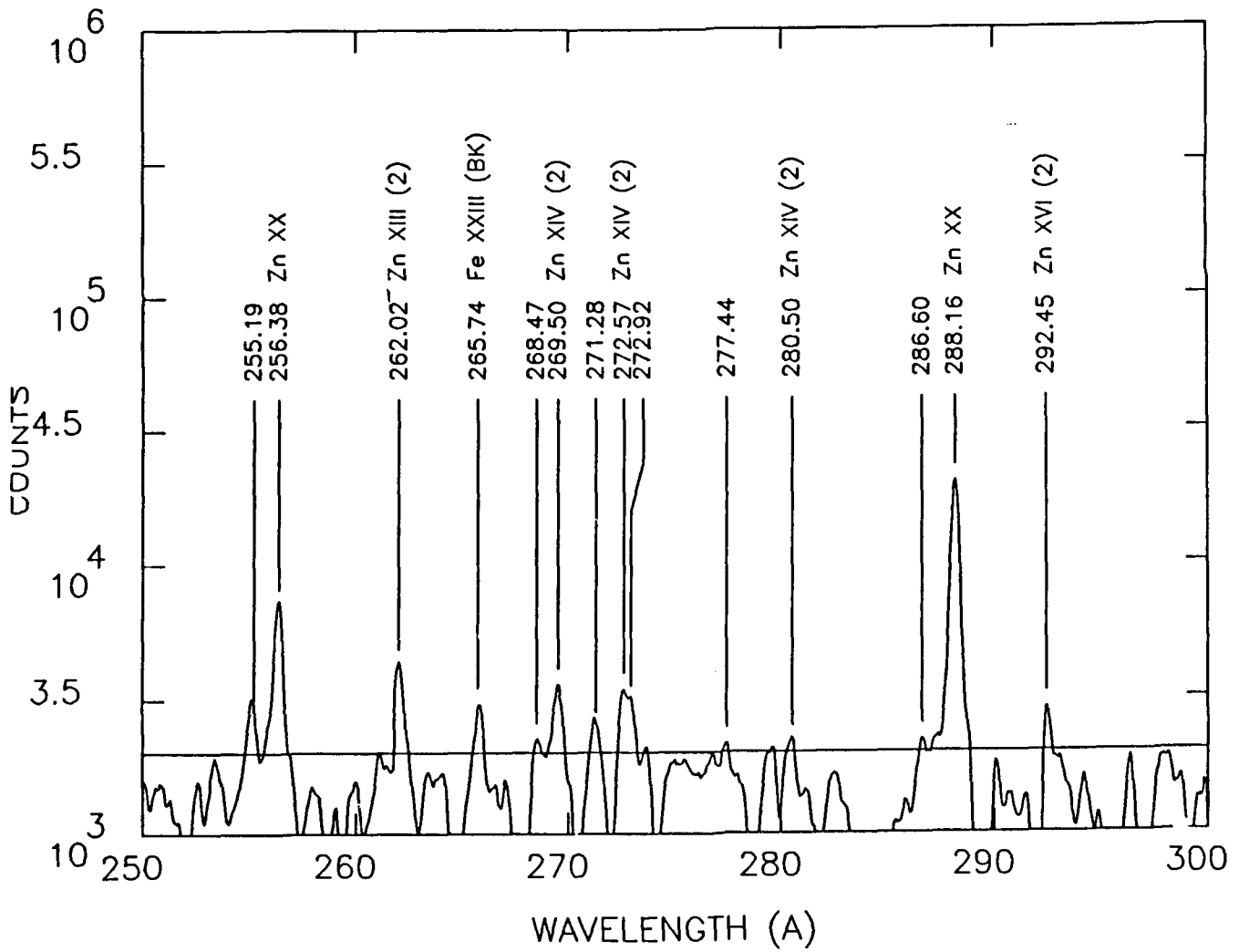
5.5
$10^5$
4.5
$10^4$
3.5
$10^3$
206.16 Zn XVIII
210.10 Zn XX
211.60 Zn XVIII
220.60 Zn XIX
223.01 Cr XXII (BK)
234.35
205
215
225
235
245
255
WAVELENGTH (A)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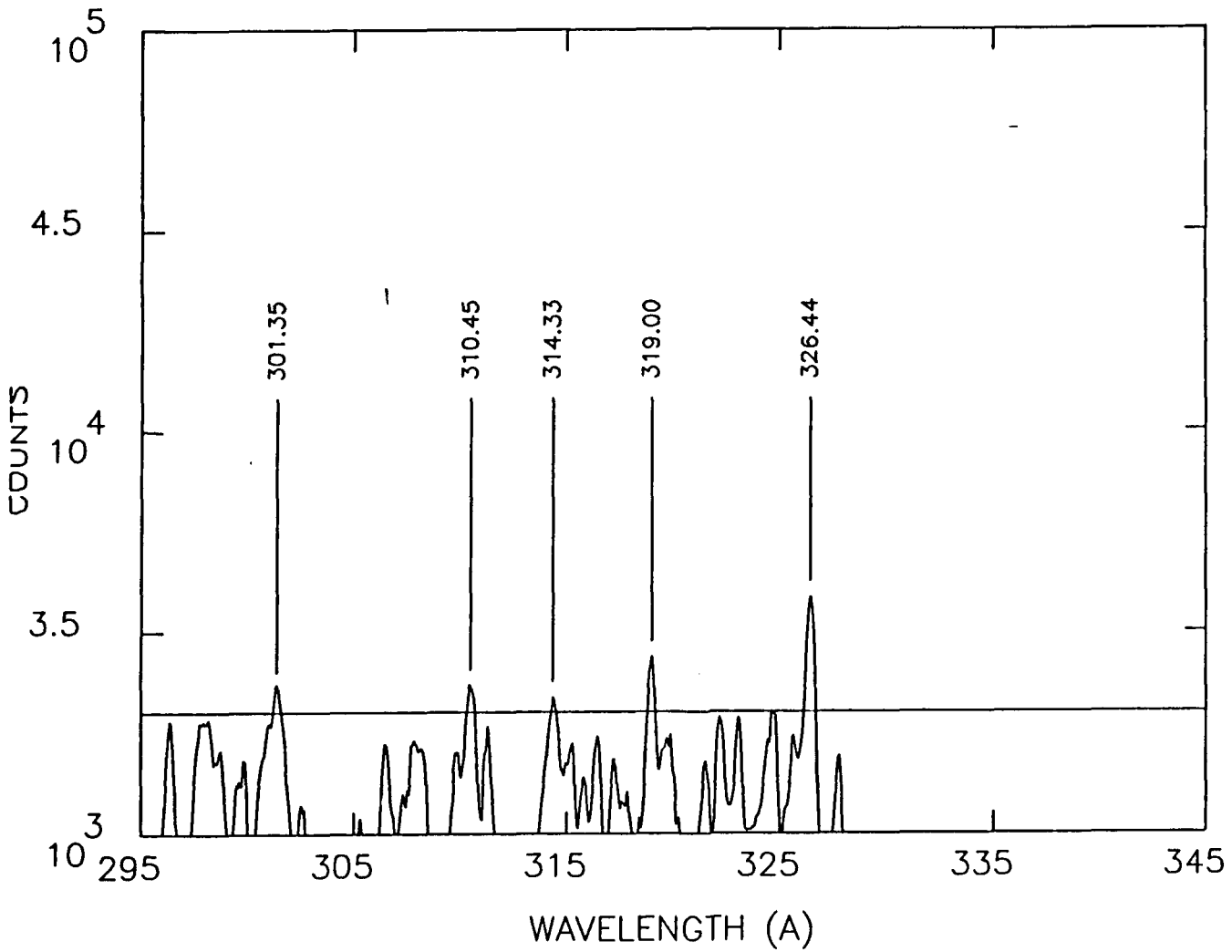
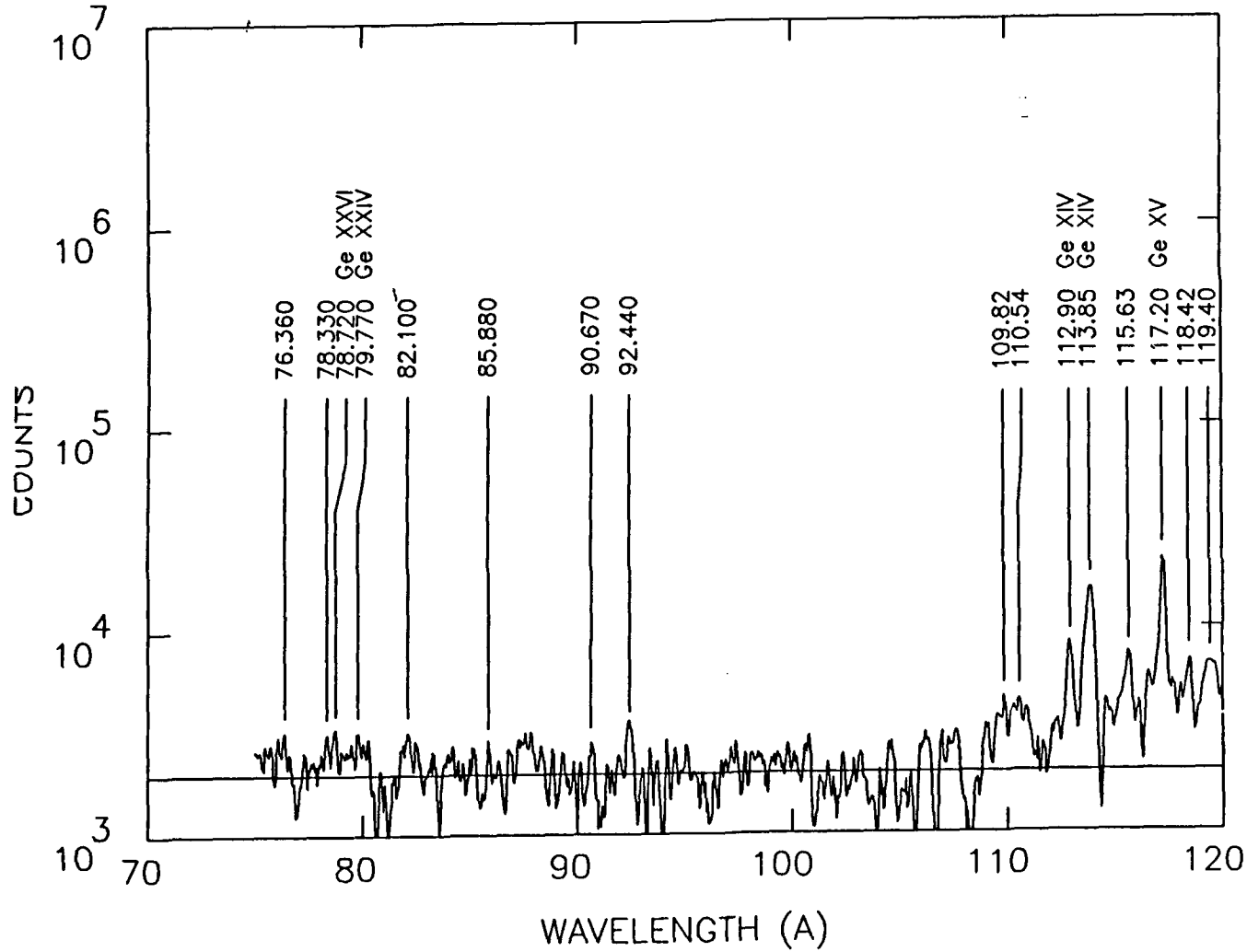
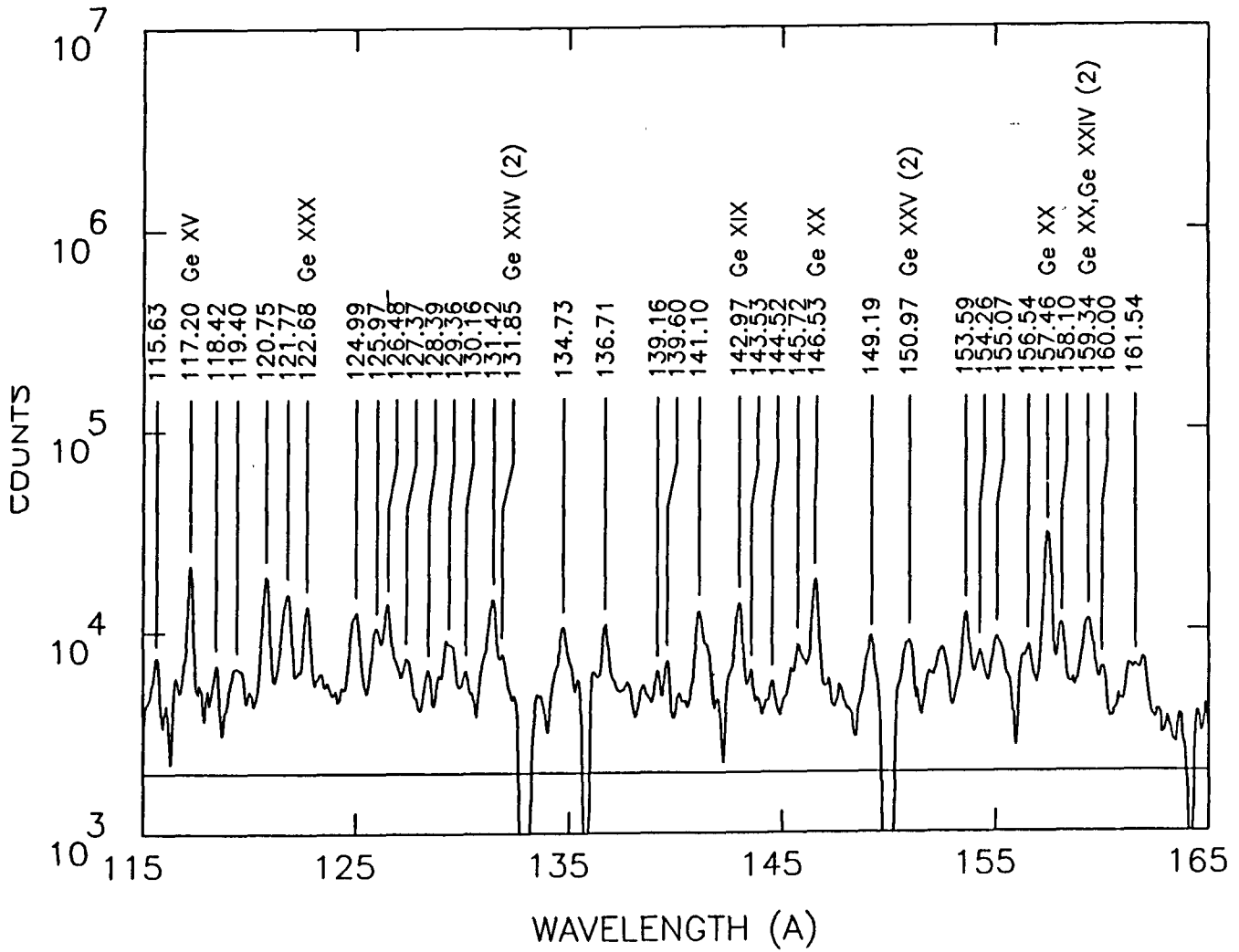
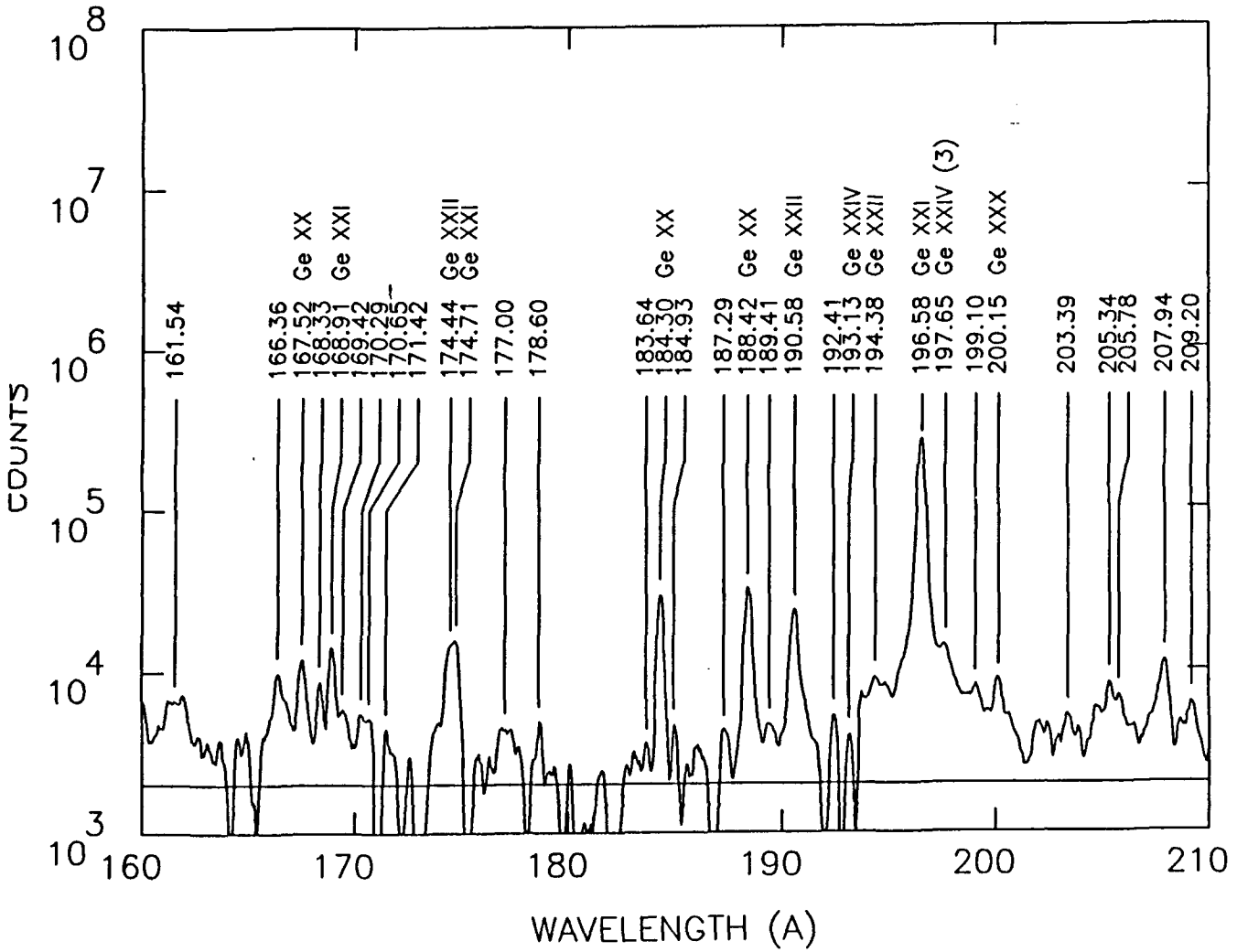
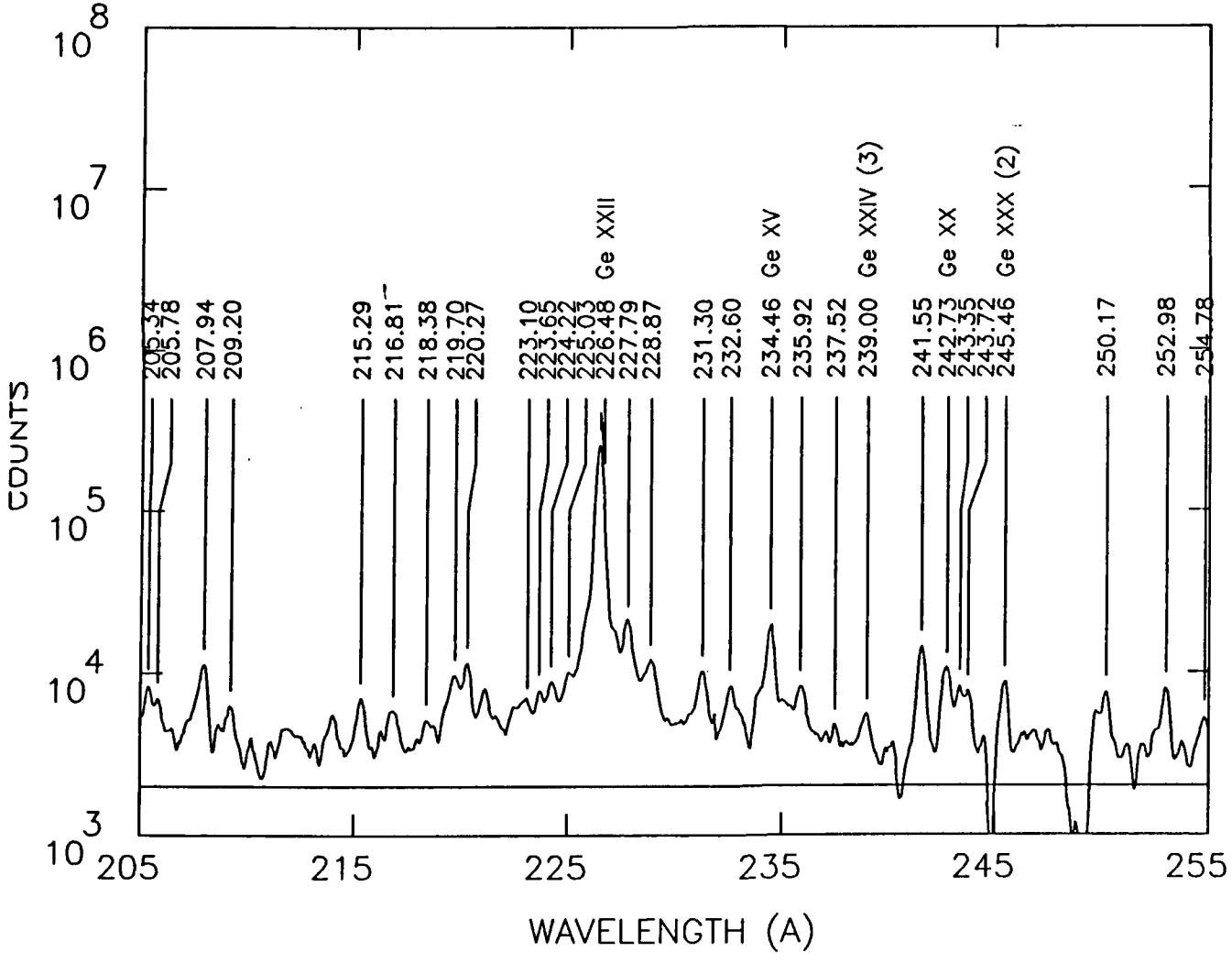
$10^6$
5.5
$10^5$
4.5
$10^4$
3.5
$10^3$
250
260
270
280
290
300
WAVELENGTH (A)
255.19
256.38 Zn XX
262.02 Zn XIII (2)
265.74 Fe XXIII (BK)
268.47
269.50 Zn XIV (2)
271.28
272.57
272.92 Zn XIV (2)
277.44
280.50 Zn XIV (2)
286.60
288.16 Zn XX
292.45 Zn XVI (2)

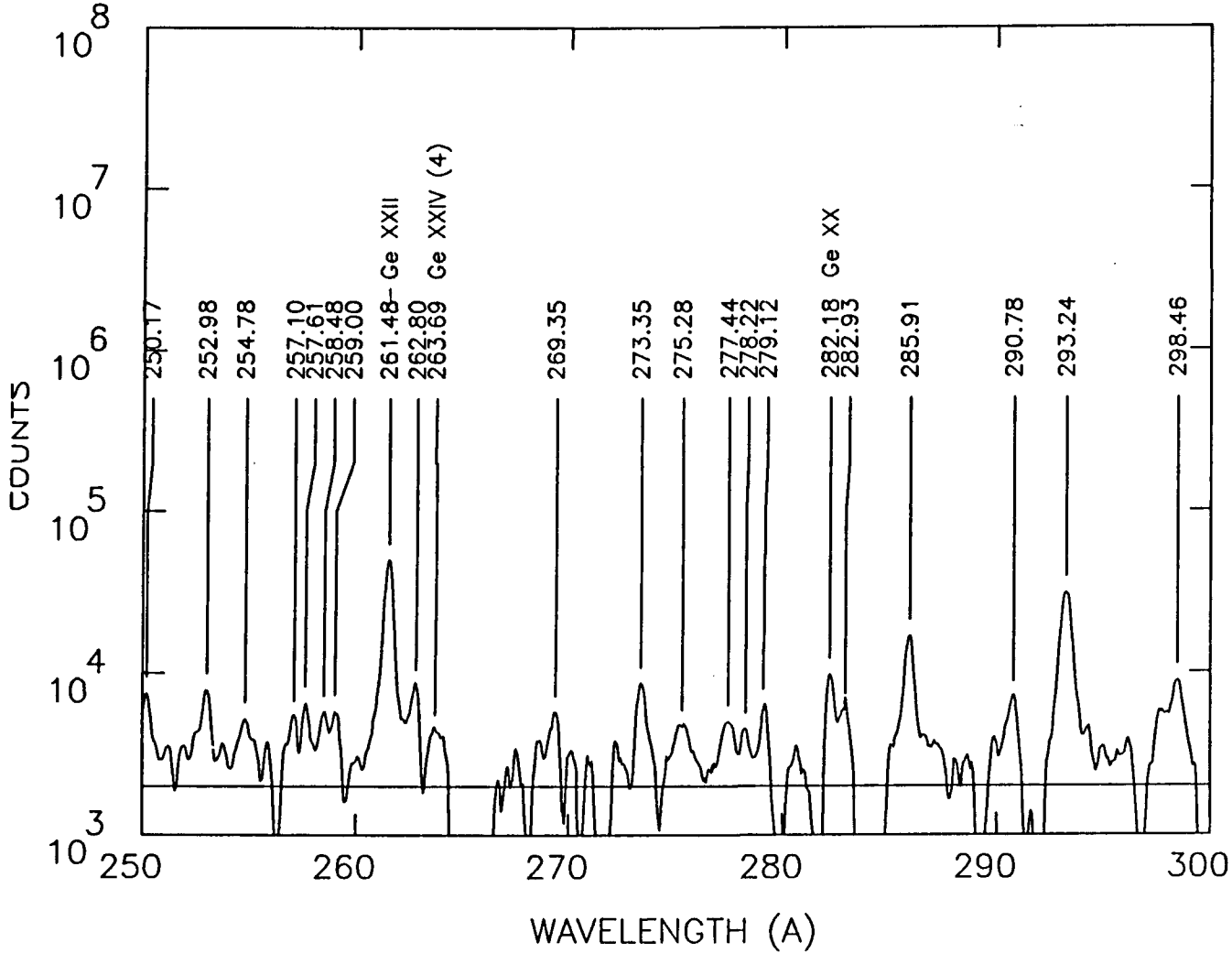

$10^5$
4.5
$10^4$
3.5
$10^3$
COUNTS
301.35
310.45
314.33
319.00
326.44
295
305
315
325
335
345
WAVELENGTH (A)

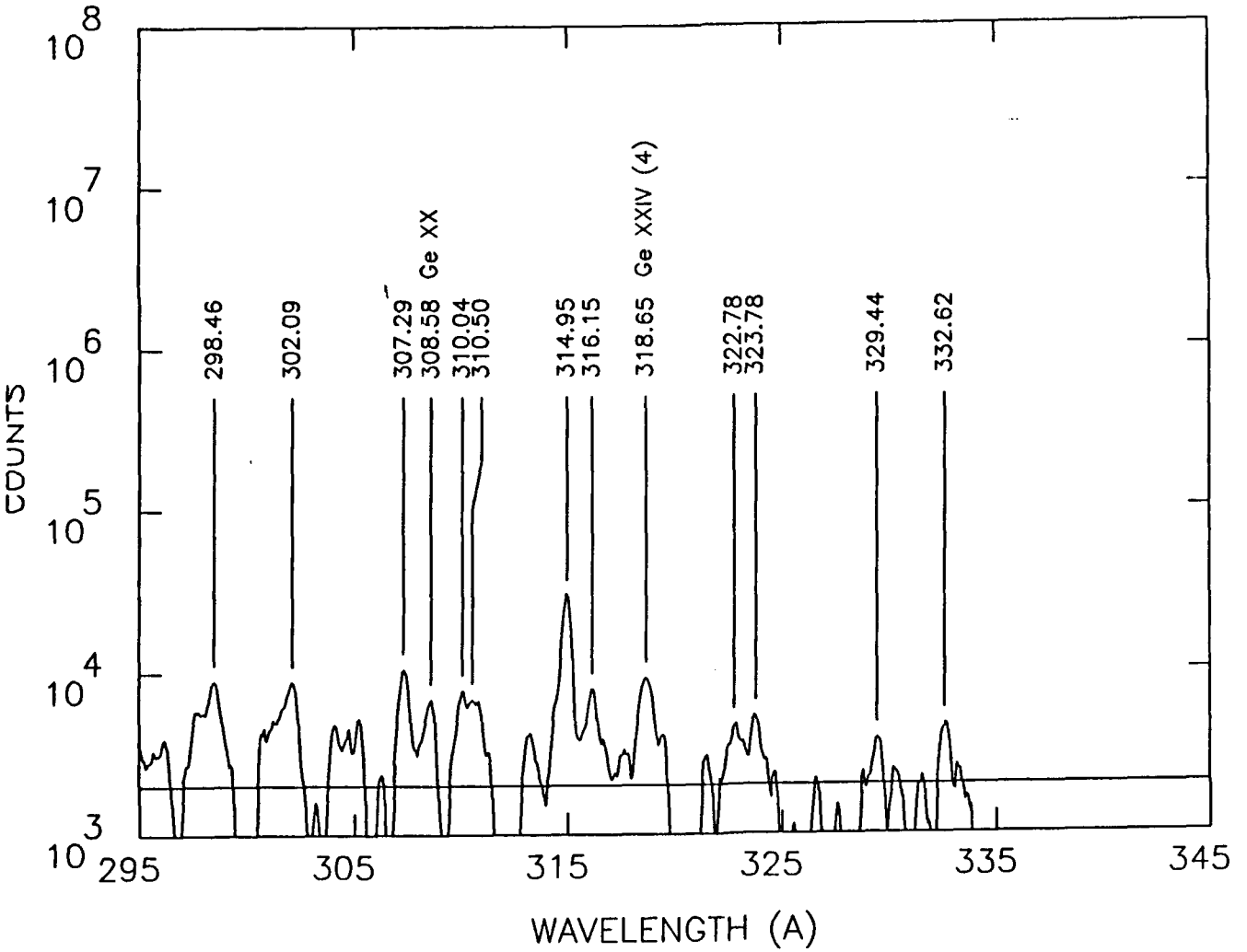

COUNTS
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
70
80
90
100
110
120
WAVELENGTH (A)
76.360
78.330
78.720
79.770
Ge XXVI
Ge XXIV
82.100
85.880
90.670
92.440
109.82
110.54
112.90
113.85
Ge XIV
Ge XIV
115.63
117.20
Ge XV
118.42
119.40


COUNTS
WAVELENGTH (A)
115.63
117.20 Ge XV
118.42
119.40
120.75
121.77
122.68 Ge XXX
124.99
125.97
126.48
127.37
128.39
129.36
130.16
131.42
131.85 Ge XXIV (2)
134.73
136.71
139.16
139.60
141.10
142.97 Ge XIX
143.53
144.52
145.72
146.53 Ge XX
149.19
150.97 Ge XXV (2)
153.59
154.26
155.07
156.54 Ge XX
157.46
158.10
159.34 Ge XX,Ge XXIV (2)
160.00
161.54


COUNTS
WAVELENGTH (A)
161.54
166.36
167.52
168.33
168.91
169.42
170.29
170.65
171.42
174.44
174.71
177.00
178.60
183.64
184.30
184.93
187.29
188.42
189.41
190.58
192.41
193.13
194.38
196.58
197.65
199.10
200.15
203.39
205.34
205.78
207.94
209.20
Ge XX
Ge XXI
Ge XXII
Ge XXI
Ge XX
Ge XX
Ge XXII
Ge XXIV
Ge XXII
Ge XXI
Ge XXIV (3)
Ge XXX

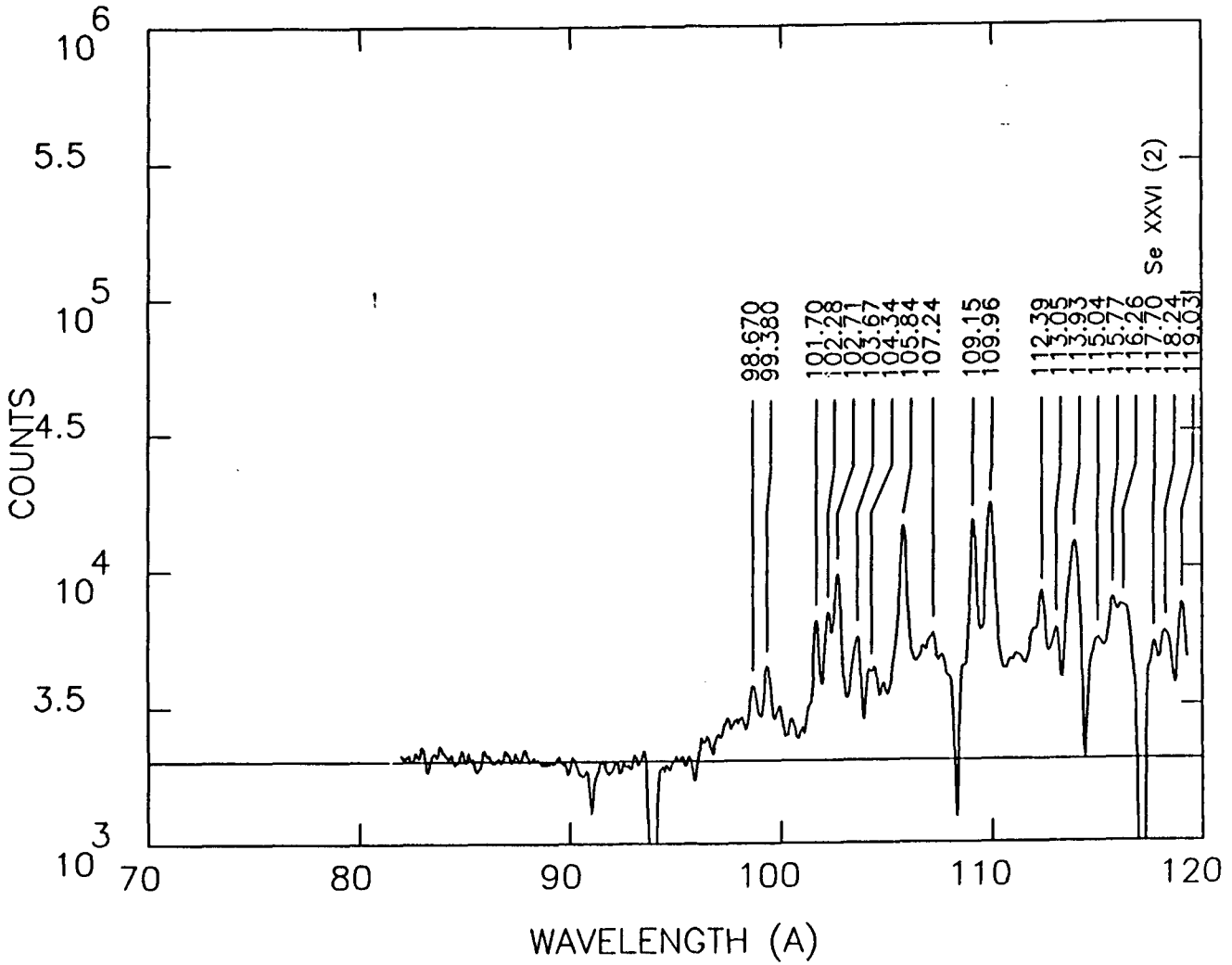

COUNTS
WAVELENGTH (A)
205.34
205.78
207.94
209.20
215.29
216.81
218.38
219.70
220.27
223.10
223.65
224.22
225.03
226.48
Ge XXII
227.79
228.87
231.30
232.60
234.46
Ge XV
235.92
237.52
239.00
Ge XXIV (3)
241.55
242.73
243.35
243.72
245.46
Ge XX
Ge XXX (2)
250.17
252.98
254.78

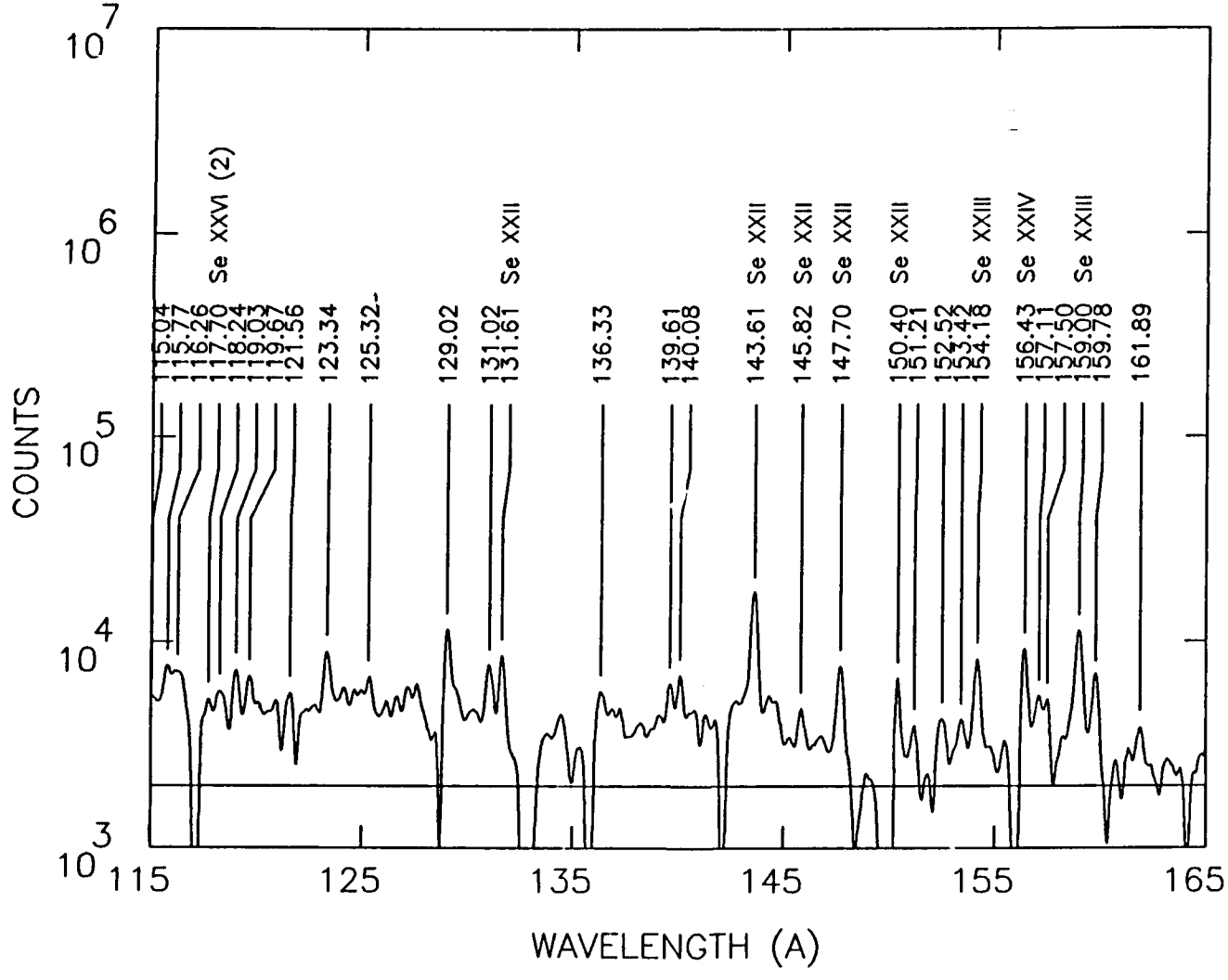

COUNTS
WAVELENGTH (A)
250.17
252.98
254.78
257.10
257.61
258.48
259.00
261.48
Ge XXII
262.80
263.69
Ge XXIV (4)
269.35
273.35
275.28
277.44
278.22
279.12
282.18
282.93
Ge XX
285.91
290.78
293.24
298.46

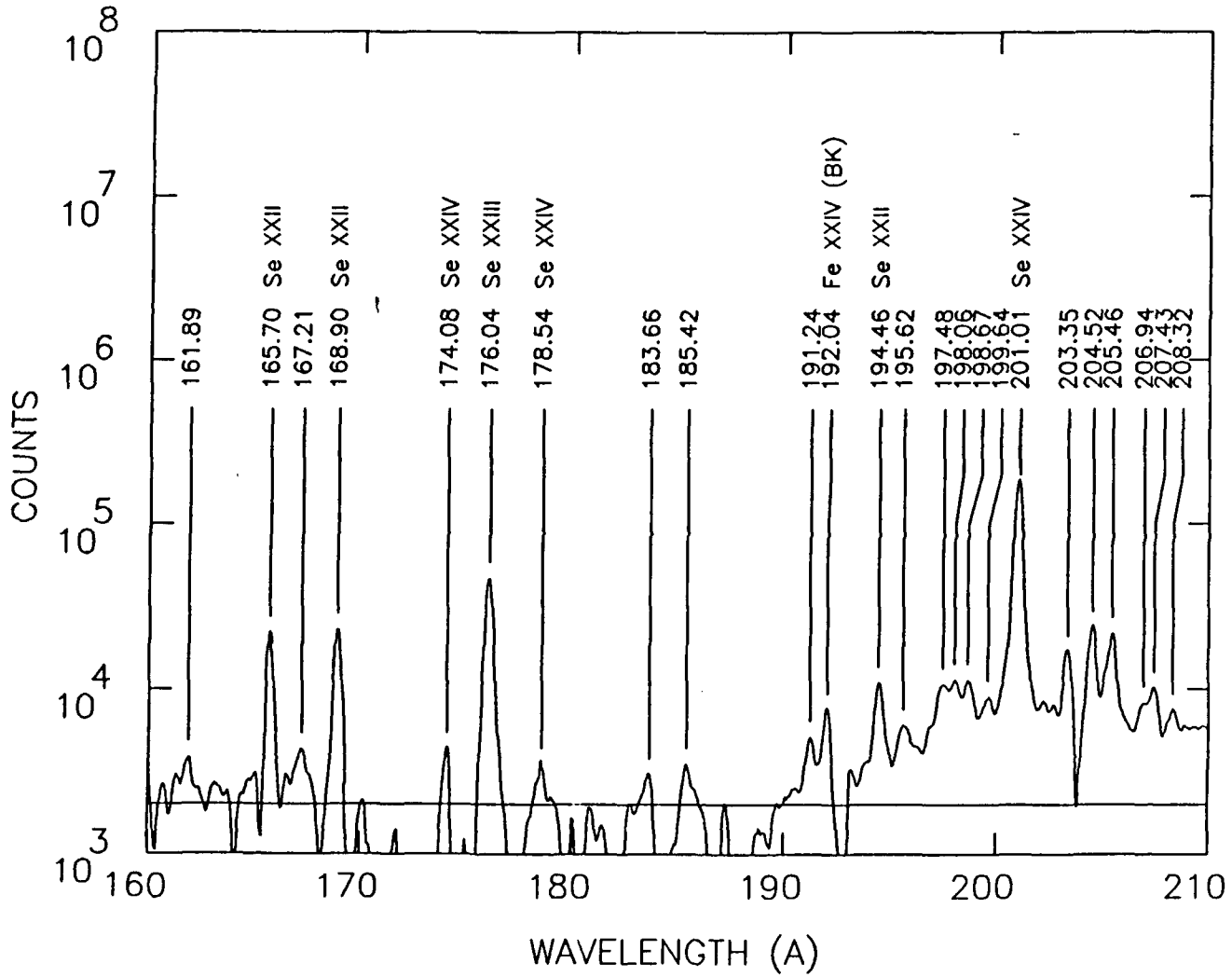

COUNTS
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
298.46
302.09
307.29
308.58 Ge XX
310.04
310.50
314.95
316.15
318.65 Ge XXIV (4)
322.78
323.78
329.44
332.62
295
305
315
325
335
345
WAVELENGTH (A)

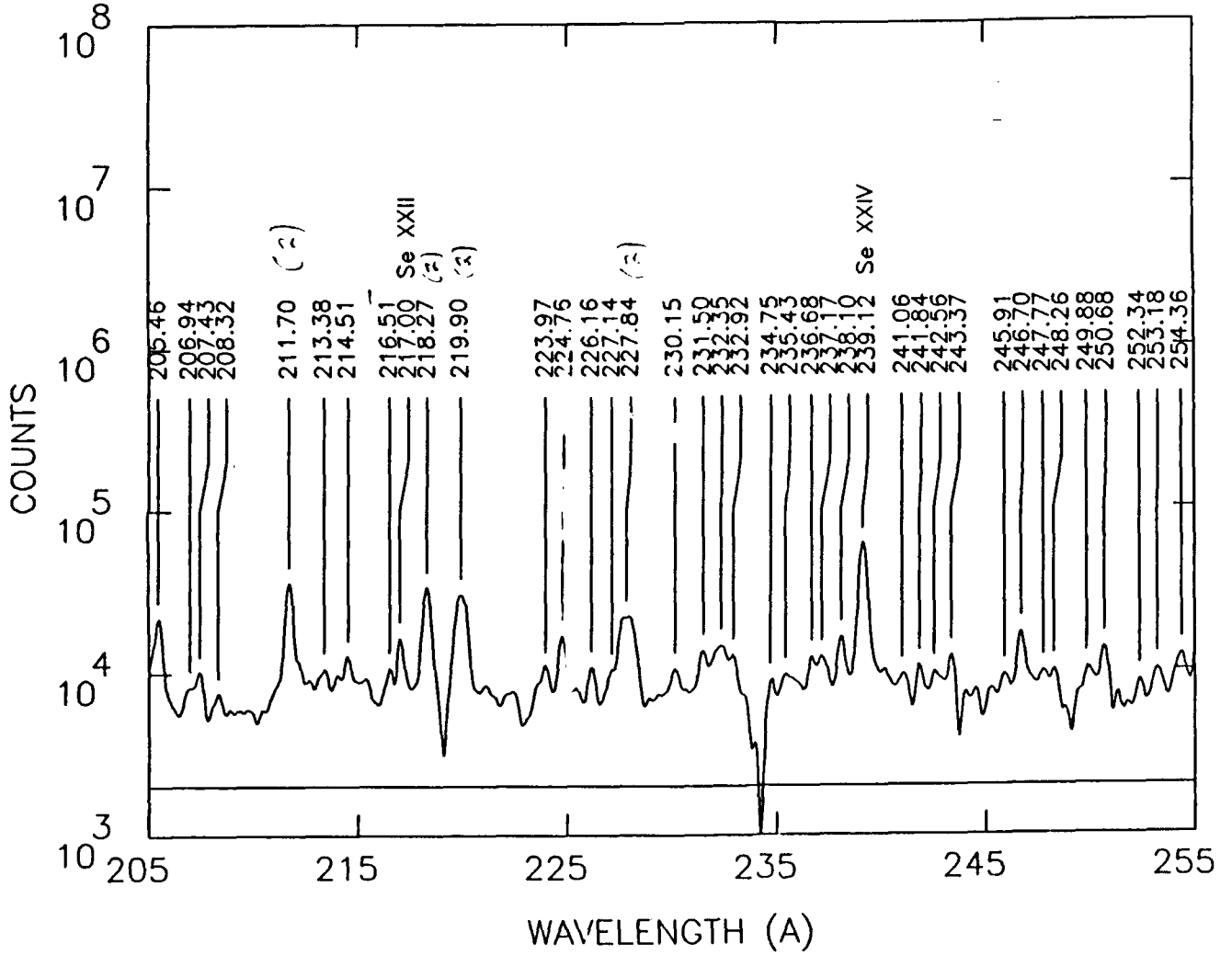
?381

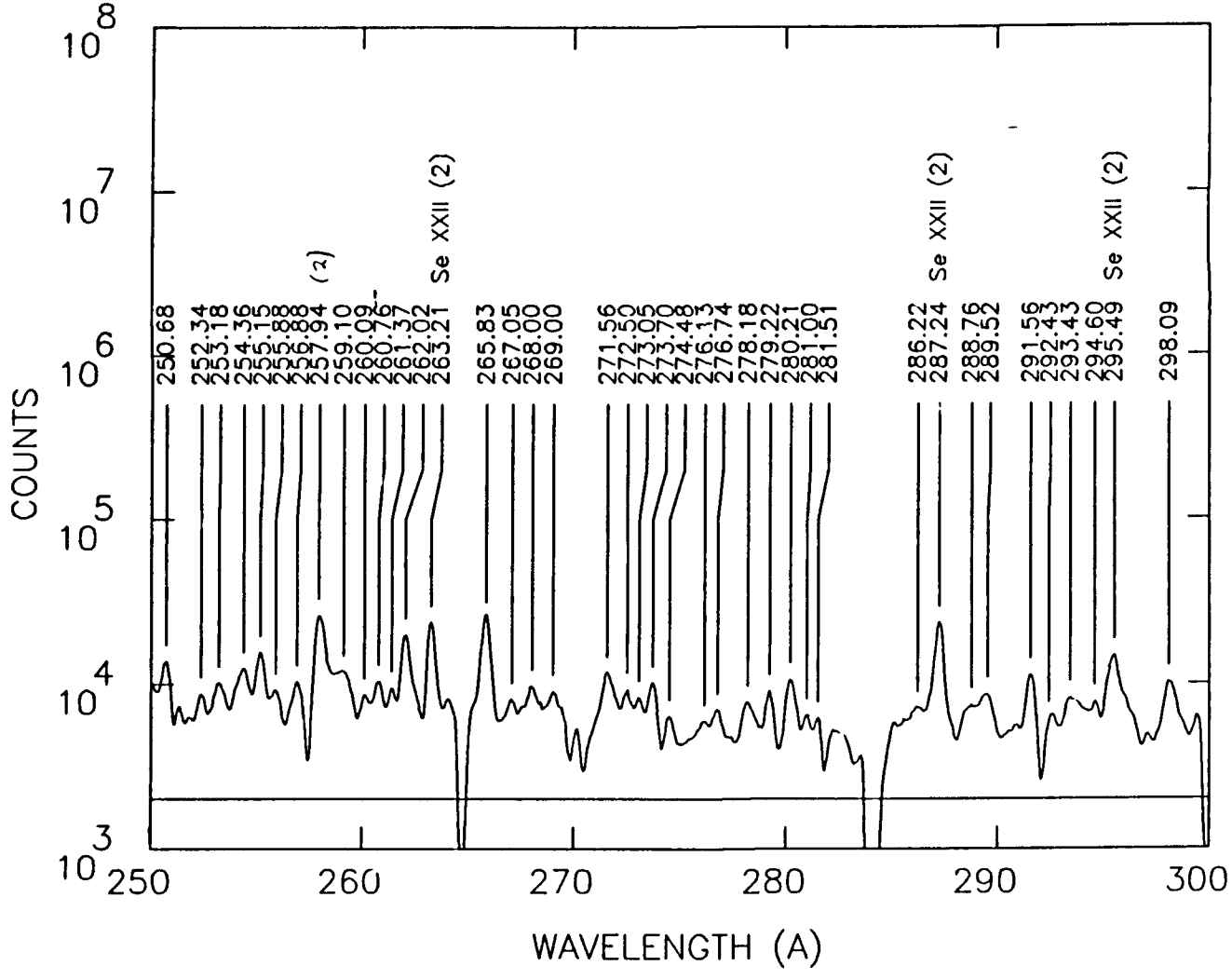
?38h

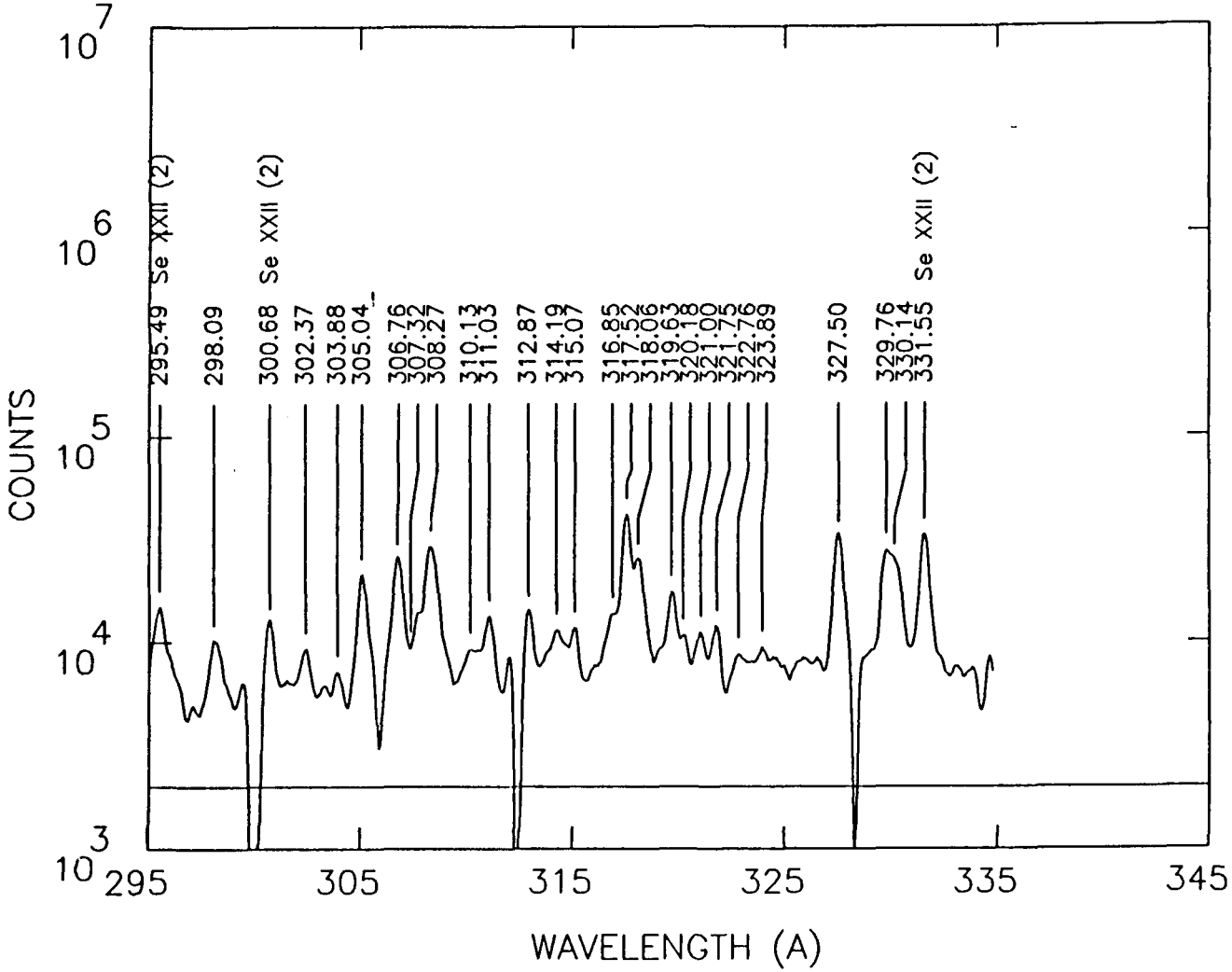

COUNTS
WAVELENGTH (A)
Se XXVI (2)
98.670
99.380
101.70
102.28
102.71
103.67
104.34
105.84
107.24
109.15
109.96
112.39
113.05
113.93
115.04
115.77
116.26
117.70
118.24
119.03

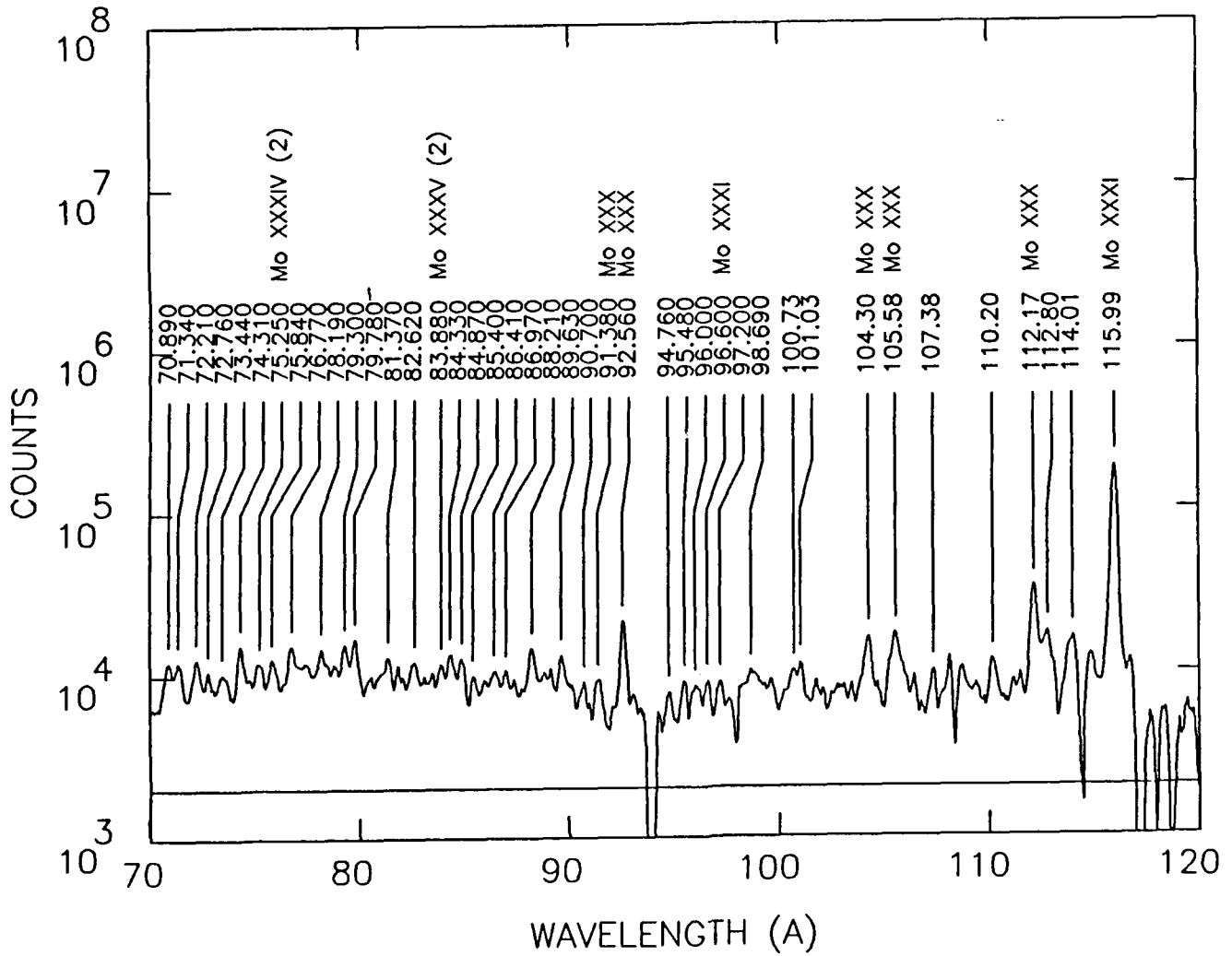

COUNTS
WAVELENGTH (A)
Se XXVI (2)
Se XXII
Se XXII
Se XXII
Se XXII
Se XXIII
Se XXIV
Se XXIII
115.04
115.77
116.26
117.70
118.24
119.03
119.67
121.56
123.34
125.32
129.02
131.02
131.61
136.33
139.61
140.08
143.61
145.82
147.70
150.40
151.21
152.52
153.42
154.18
156.43
157.11
157.50
159.00
159.78
161.89

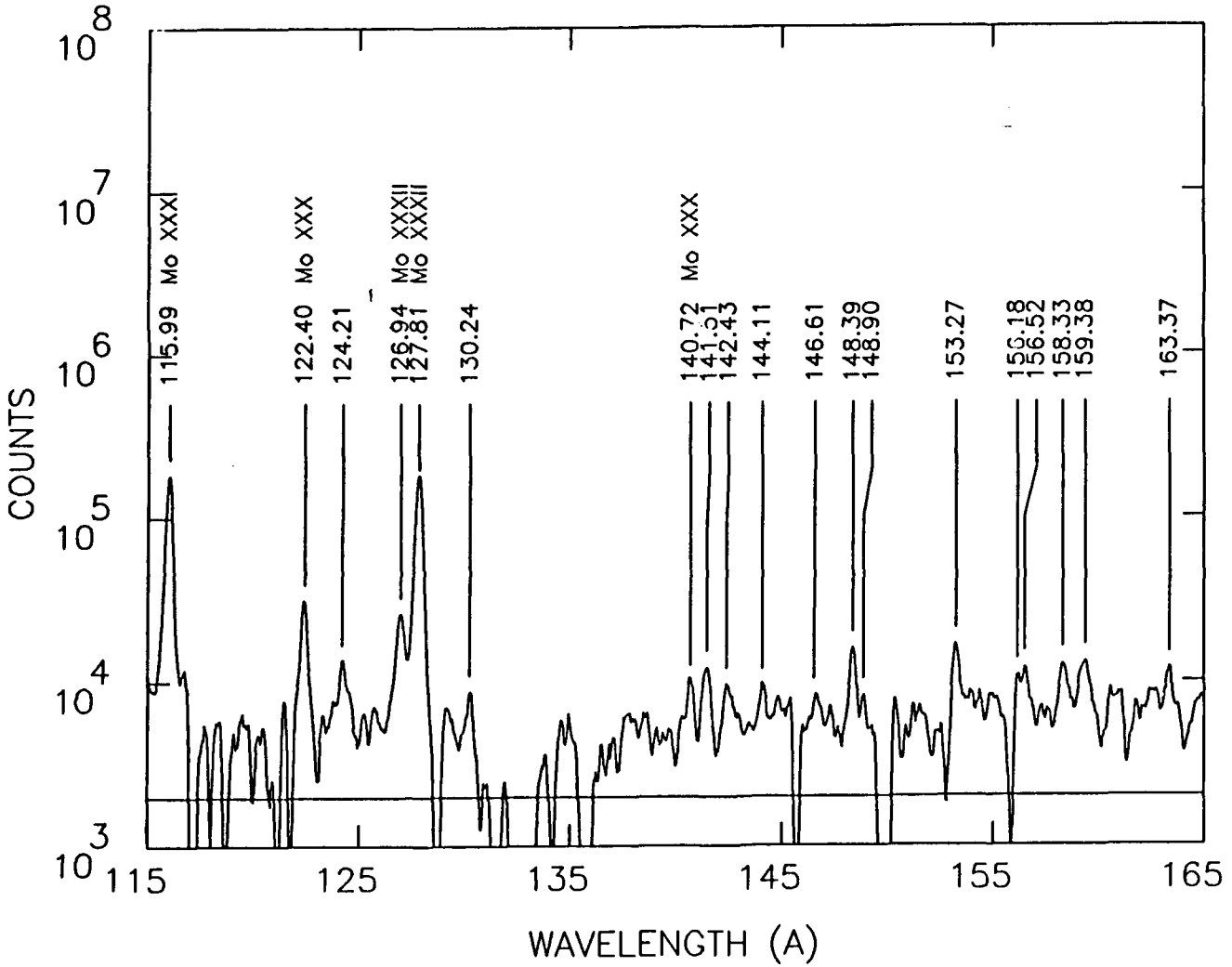

COUNTS
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
160
170
180
190
200
210
WAVELENGTH (A)
161.89
165.70 Se XXII
167.21
168.90 Se XXII
174.08 Se XXIV
176.04 Se XXIII
178.54 Se XXIV
183.66
185.42
191.24
192.04 Fe XXIV (BK)
194.46 Se XXII
195.62
197.48
198.06
198.67
199.64
201.01 Se XXIV
203.35
204.52
205.46
206.94
207.43
208.32

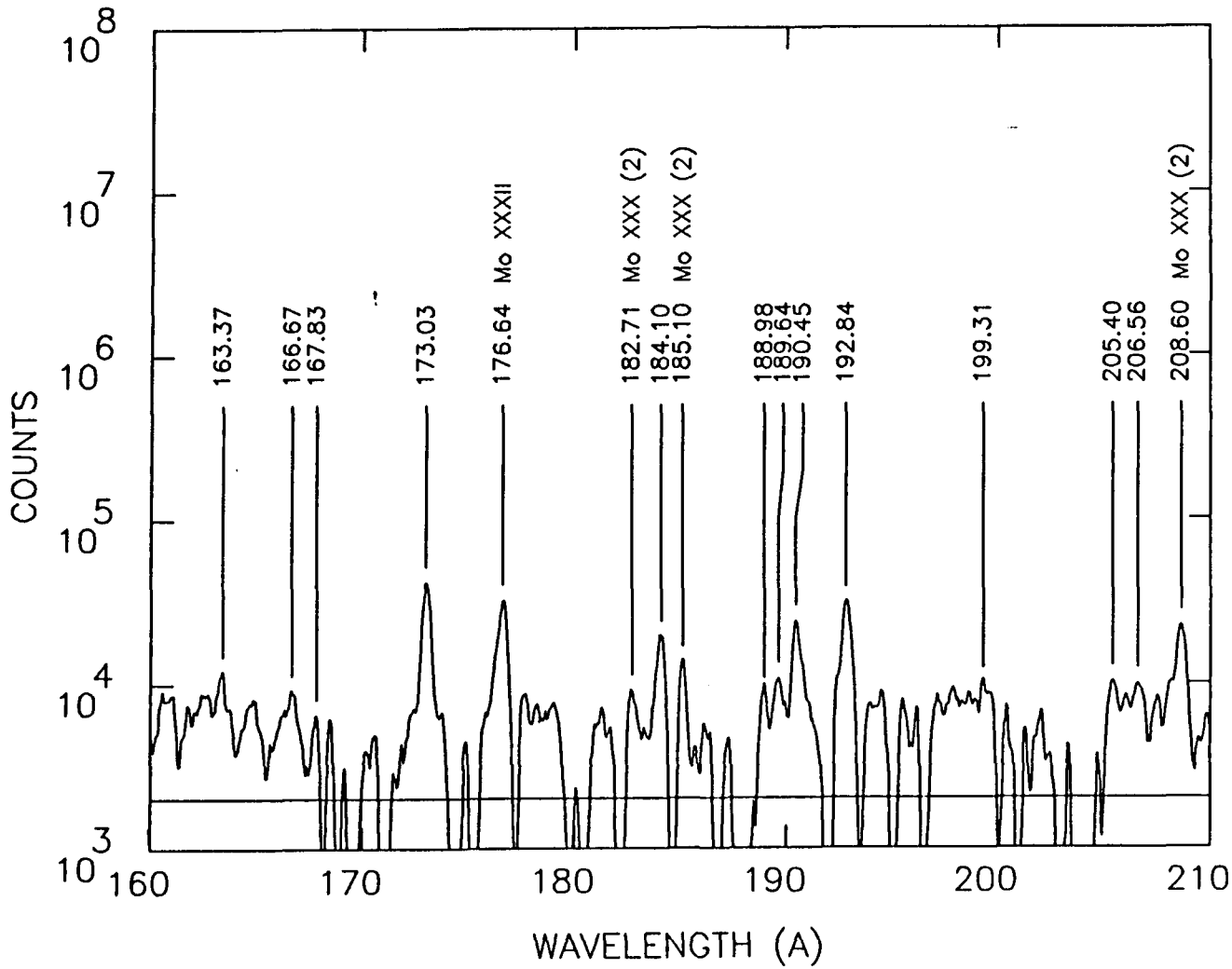

COUNTS
WAVELENGTH (A)
Se XXII
Se XXIV

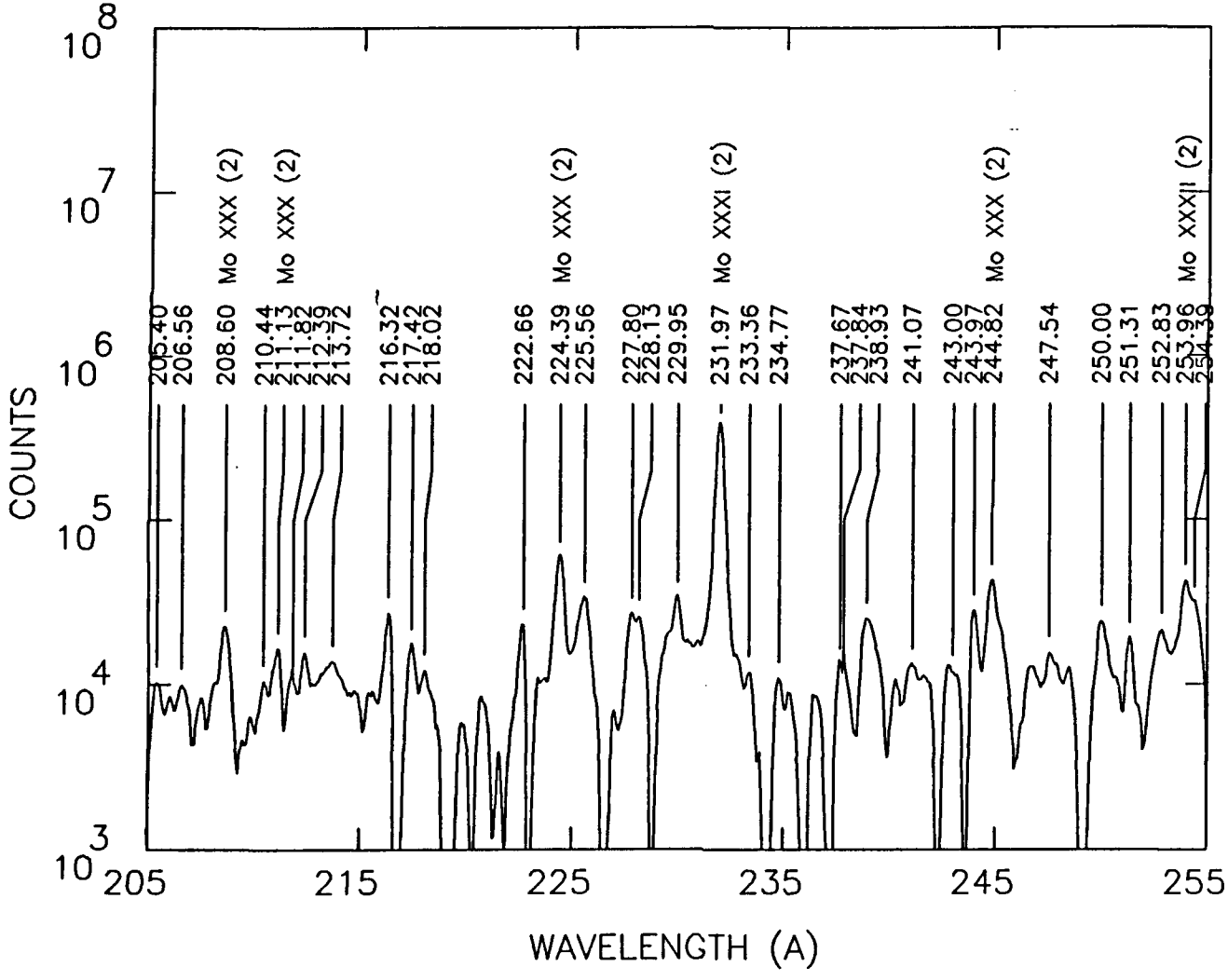

COUNTS
WAVELENGTH (A)
250.68
252.34
253.18
254.36
255.15
255.88
256.94 (2)
257.94
259.10
260.09
260.76
261.37
262.02
263.21 Se XXII (2)
265.83
267.05
268.00
269.00
271.56
272.50
273.05
273.70
274.48
276.13
276.74
278.18
279.22
280.21
281.00
281.51
286.22
287.24 Se XXII (2)
288.76
289.52
291.56
292.43
293.43
294.60
295.49 Se XXII (2)
298.09

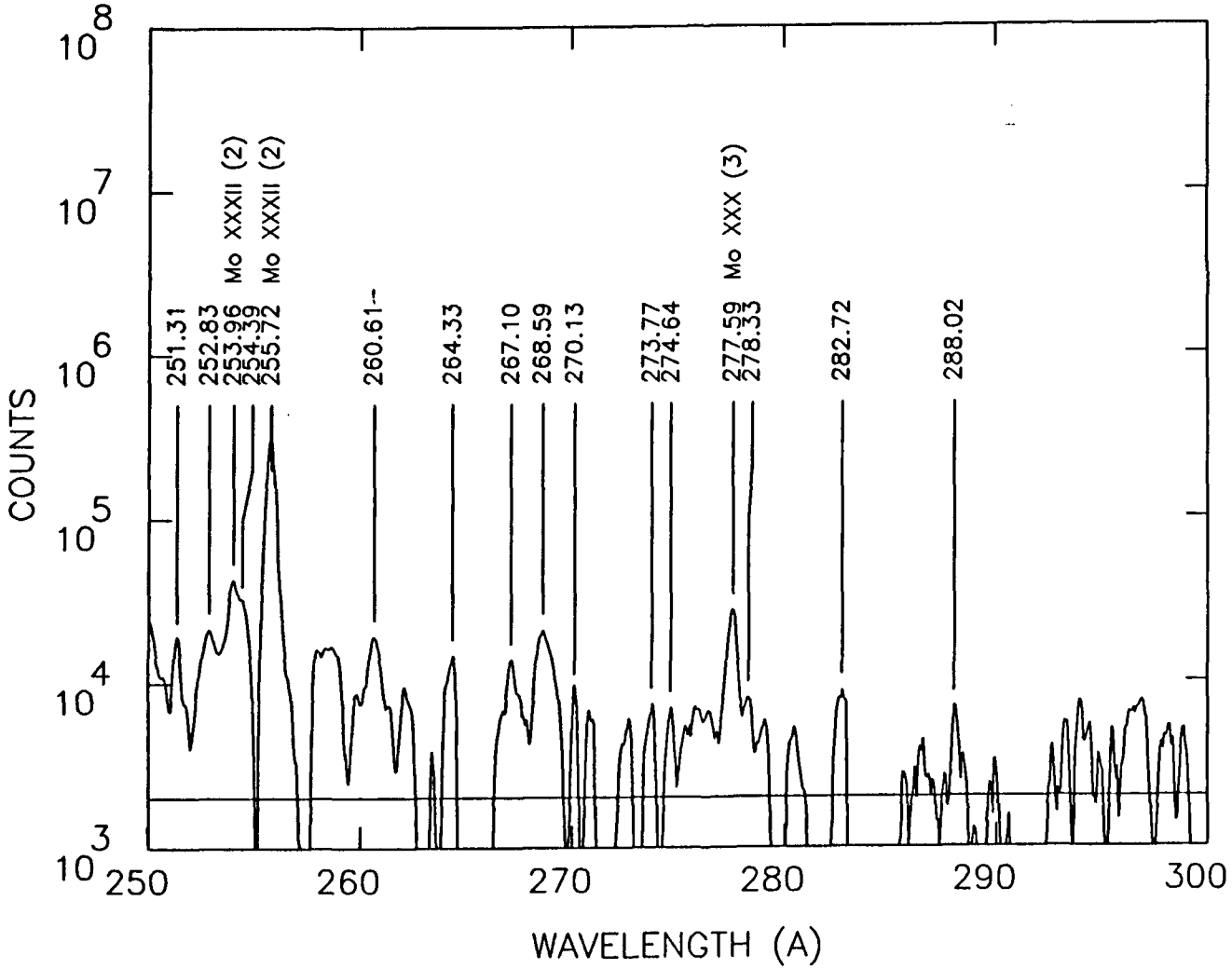

COUNTS
WAVELENGTH (A)
Se XXII (2)
Se XXII (2)
Se XXII (2)
295.49
298.09
300.68
302.37
303.88
305.04
306.76
307.32
308.27
310.13
311.03
312.87
314.19
315.07
316.85
317.52
318.06
319.63
320.18
321.00
321.75
322.76
323.89
327.50
329.76
330.14
331.55


COUNTS
WAVELENGTH (A)
Mo XXXIV (2)
Mo XXXV (2)
Mo XXX
Mo XXX
Mo XXXI
Mo XXX
Mo XXX
Mo XXX
Mo XXXI
70.890
71.340
72.210
72.760
73.440
74.310
75.250
75.840
76.770
78.190
79.300
79.780
81.370
82.620
83.880
84.330
84.870
85.400
86.410
86.970
88.210
89.630
90.700
91.380
92.560
94.760
95.480
96.000
96.600
97.200
98.690
100.73
101.03
104.30
105.58
107.38
110.20
112.17
112.80
114.01
115.99


COUNTS
10^8
10^7
10^6
10^5
10^4
10^3
115
125
135
145
155
165
WAVELENGTH (A)
115.99 Mo XXXI
122.40 Mo XXX
124.21
126.94 Mo XXXII
127.81 Mo XXXII
130.24
140.72 Mo XXX
141.51
142.43
144.11
146.61
148.39
148.90
153.27
156.18
156.52
158.33
159.38
163.37


COUNTS
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
160
170
180
190
200
210
WAVELENGTH (A)
163.37
166.67
167.83
173.03
176.64 Mo XXXII
182.71 Mo XXX (2)
184.10
185.10 Mo XXX (2)
188.98
189.64
190.45
192.84
199.31
205.40
206.56
208.60 Mo XXX (2)


COUNTS
WAVELENGTH (A)
Mo XXX (2)
Mo XXX (2)
Mo XXX (2)
Mo XXXI (2)
Mo XXX (2)
Mo XXXII (2)


COUNTS
WAVELENGTH (A)
251.31
252.83
253.96
254.39
255.72
Mo XXXII (2)
Mo XXXII (2)
260.61
264.33
267.10
268.59
270.13
273.77
274.64
277.59
278.33
Mo XXX (3)
282.72
288.02

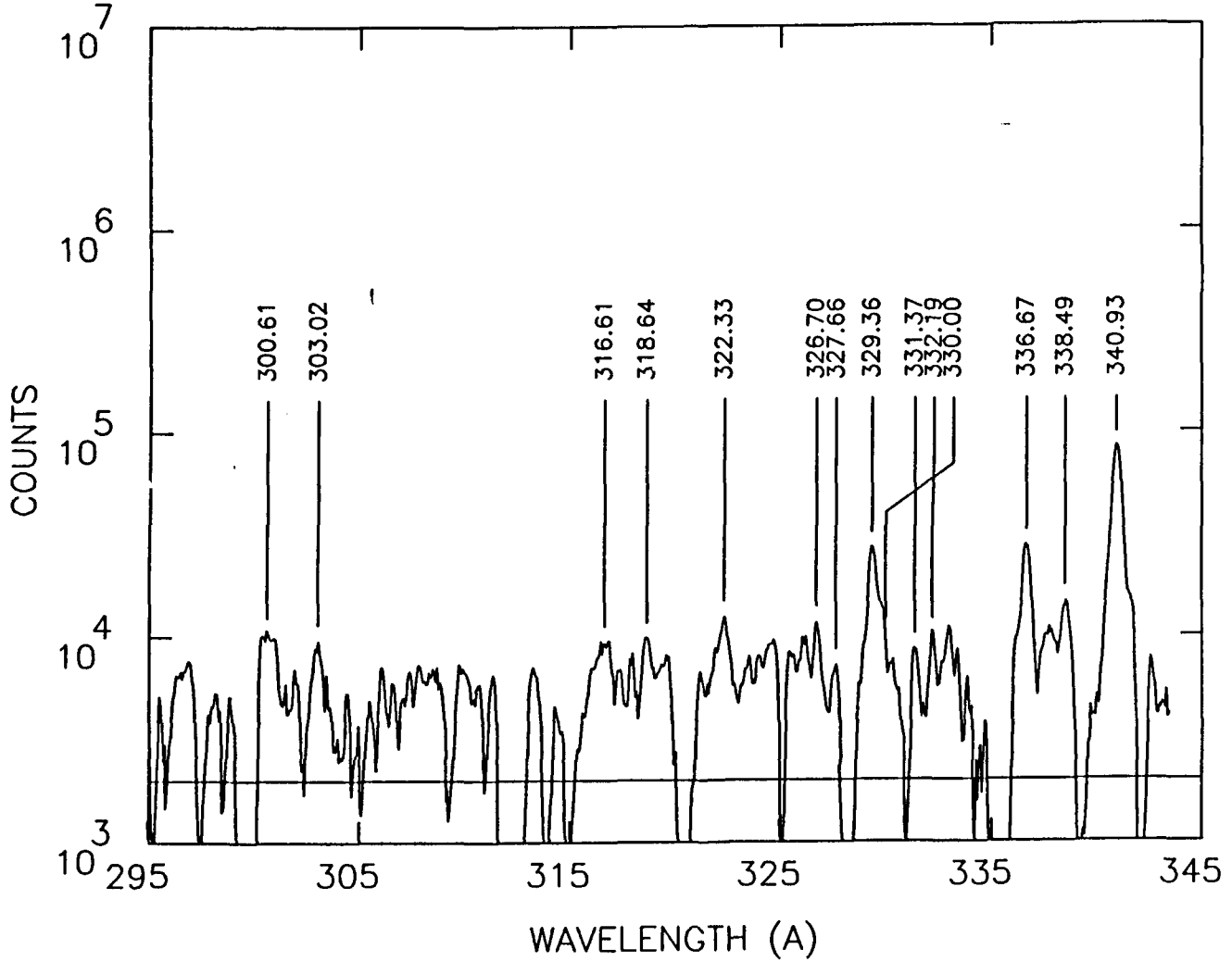

COUNTS
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
300.61
303.02
316.61
318.64
322.33
326.70
327.66
329.36
331.37
332.19
330.00
336.67
338.49
340.93
295
305
315
325
335
345
WAVELENGTH (A)

Table I. Classification of Spectral Lines, Presently Measured Wavelengths, and Previous Wavelengths.

| Transition | Wavelengths (in Angstroms) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pres | Prev | Pres | Prev | Pres | Prev | Pres | Prev | Pres | Prev | Pres | Prev |
| **Li I** | | | | | | | | | | | | |
| | Fe XXIV | | Ni XXVI | | Zn XXVIII | | Ge XXX | | Se XXXII | | Mo XL | |
| 2s-2p | | | | | | | | | | | | |
| $^2S_{1/2}$-$^2P_{3/2}$ | 192.01[B] | 192.01[a] | 165.35 | 165.38[a] | | 142.44[a] | 122.68 | 122.66[a] | | 105.64[a] | | |
| $^2S_{1/2}$-$^2P_{1/2}$ | 255.08? | 255.08[a] | 234.14[B] | 234.09[a] | | 215.99[a] | 200.15 | 200.18[a] | | 186.25[a] | | |
| **Be I** | | | | | | | | | | | | |
| | Fe XXIII | | Ni XXV | | Zn XXVII | | Ge XXIX | | Se XXXI | | Mo XXXIX | |
| $2s^2$-2s2p | | | | | | | | | | | | |
| $^1S_0$-$^1P_1$ | 132.88 | 132.88[a] | 117.93[B] | 117.94[a] | | 104.67[a] | | 92.81[a] | | 82.18[a] | | |
| $^1S_0$-$^3P_1$ | 263.73? | 263.74[a] | 238.89 | 238.86[a] | | 217.66[a] | | 199.46[a] | | 183.75[a] | | |

B I

| | Fe XXII | | Ni XXIV | | Zn XXVI | | Ge XXVIII | | Se XXX | Mo XXXVIII |
|---|---|---|---|---|---|---|---|---|---|---|
| $2s^2 2p - 2s 2p^2$ | | | | | | | | | | |
| $^2P_{1/2}-{}^2P_{3/2}$ | 100.77 | 100.77[b] | | 87.46[b] | | 75.82[b] | | 65.64[b] | 56.74[b] | |
| $^2P_{1/2}-{}^2P_{1/2}$ | 102.22[B] | 102.22[b] | | 88.61[b] | | 76.8[b] | | 66.4[b] | 57.3[b] | |
| $^2P_{3/2}-{}^2P_{3/2}$ | 114.41 | 114.41[b] | 102.12[B] | 102.10[b] | | 91.17[b] | | 81.37[b] | 72.55[b] | |
| $^2P_{3/2}-{}^2P_{1/2}$ | 116.25 | 116.27[b] | | 103.68[b] | | 92.6[b] | | 82.6[b] | 73.5[b] | |
| $^2P_{1/2}-{}^2S_{1/2}$ | 117.13 | 117.18[b] | 104.66[B] | 104.63[b] | 93.51 | 93.5[b] | | 83.5[b] | 74.6[b] | |
| $^2P_{1/2}-{}^2D_{3/2}$ | 135.76 | 135.76[b] | 118.49 | 118.47[b] | 103.72 | 103.60[b] | 90.67 | 90.73[b] | 79.56[b] | |
| $^2P_{3/2}-{}^2D_{5/2}$ | 155.94 | 155.94[b] | 138.73 | 138.73[b] | 123.23 | 123.20[b] | | 109.04[b] | 96.12[b] | |
| $^2P_{1/2}-{}^4P_{1/2}$ | 247.19? | 247.20[b] | 218.43 | 218.43[b] | | 194.32[b] | | 174.05[b] | 156.97[b] | |

C I

| | FeXXI | | Ni XXIII | | Zn XXV | | Ge XXVII | Se XXIX | Mo XXXVII |
|---|---|---|---|---|---|---|---|---|---|
| $2s^2 2p^2 - 2s 2p^3$ | | | | | | | | | |
| $^3P_0 - ^3S_1$ | | 91.27[c] | 79.95 | 79.97[c] | | 70.02[c] | 61.21[c] | 53.41[c] | |
| $^3P_1 - ^3S_1$ | 97.86 | 97.86[c] | 87.62 | 87.67[c] | 78.70 | 78.71[d] | 70.74[c] | 63.55[c] | |
| $^1D_2 - ^1P_1$ | 98.36[B] | 98.36[c] | | 87.99[c] | | 78.89[c] | 70.79[c] | 63.52[c] | |
| $^3P_2 - ^1D_2$ | 99.02 | 99.03[c] | | 87.53[c] | 77.09 | 77.11[d] | 67.66[c] | 59.05[c] | |
| $^3P_2 - ^3S_1$ | 102.22[B] | 102.21[c] | 91.89 | 91.87[c] | 82.69 | 82.64[d] | 74.30[d] | 66.72[c] | |
| $^3P_0 - ^3P_1$ | | 108.11[c] | 92.71 | 92.72[c] | | 79.48[c] | 68.07[c] | 58.32[c] | |
| $^1D_2 - ^1D_2$ | 113.33 | 113.29[c] | 102.12[B] | 102.07[c] | | 92.15[c] | 83.14[c] | 74.80[c] | |
| $^3P_1 - ^3P_1$ | 117.47 | 117.49[c] | | 103.22[c] | | 90.84[c] | 80.06[c] | 70.63[c] | |
| $^3P_1 - ^3P_0$ | 118.67[B] | 118.69[c] | 104.66[B] | 104.70[c] | | 92.52[c] | 81.84[c] | 72.42[c] | |
| $^3P_2 - ^3P_2$ | 121.18 | 121.19[c] | 106.06[B] | 106.05[c] | 92.89 | 92.85[d] | 81.37[d] | 71.56[c] | |
| $^3P_2 - ^3P_1$ | 123.80 | 123.82[c] | | 109.09[c] | | 96.11[c] | 84.66[c] | 74.57[c] | |
| $^3P_0 - ^3D_1$ | 128.72 | 128.73[c] | 111.82 | 111.83[c] | 97.44 | 97.45[d] | 85.08[c] | 74.49[c] | |
| $^3P_1 - ^3D_2$ | 142.12 | 142.14[c] | 126.55 | 126.59[c] | 113.00 | 112.98[c] | 100.82[c] | 89.77[c] | |
| $^3P_2 - ^3D_3$ | 145.69 | 145.70[c] | 128.32 | 128.32[c] | | 112.93[c] | 99.28[c] | 87.19[c] | |
| $^1D_2 - ^3D_3$ | 178.89 | 178.85[c] | | 162.19[c] | | 148.32[c] | 136.60[c] | 126.54[c] | |

N I

| | Fe XX | | Ni XXII | | Zn XXIV | | Ge XXVI | | Se XXVIII | Mo XXXVI |
|---|---|---|---|---|---|---|---|---|---|---|
| $2s^2 2p^3 - 2s 2p^4$ | | | | | | | | | | |
| $^4S_{3/2} - ^2P_{3/2}$ | | 80.49[f] | | 71.49[f] | | 63.35[d] | | 55.93[f] | 49.20[f] | |
| $^2D_{3/2} - ^2P_{1/2}$ | 83.24 | 83.23[f] | | 72.52[f] | | 63.33[f] | | 55.38[f] | 48.46[f] | |
| $^2D_{3/2} - ^2P_{3/2}$ | 90.56 | 90.59[f] | | 80.56[f] | 71.89 | 71.92[d] | | 64.34[f] | 57.68[f] | |
| $^2D_{5/2} - ^2P_{3/2}$ | | 93.78[f] | 84.11 | 84.07[f] | 75.59 | 75.50[d] | | 67.84[d] | 60.90[f] | |
| $^2D_{3/2} - ^2S_{1/2}$ | 94.67 | 94.64[f] | | 84.25[f] | | 75.29[d] | | 67.43[d] | 60.40[f] | |
| $^2P_{3/2} - ^2P_{1/2}$ | 98.36[B] | 98.35[f] | 88.02 | 88.01[f] | | 78.98[d] | | 70.99[d] | 63.83[f] | |
| $^2P_{1/2} - ^2S_{1/2}$ | 106.94 | 106.96[f] | 95.91[B] | 95.98[f] | | 86.27[d] | | 77.51[d] | 69.41[f] | |
| $^2P_{3/2} - ^2P_{3/2}$ | 108.80 | 108.80[f] | | 100.13[f] | | 92.77[f] | | 86.41[f] | 80.84[f] | |
| $^2D_{3/2} - ^2D_{3/2}$ | 110.64 | 110.63[f] | 98.20 | 98.18[f] | 87.69 | 87.69[d] | 78.72 | 78.70[d] | 70.87[f] | |
| $^2D_{5/2} - ^2D_{5/2}$ | 113.33 | 113.35[f] | 100.60 | 100.61[f] | 89.50 | 89.47[d] | | 79.64[d] | 70.84[f] | |
| $^4S_{3/2} - ^4P_{1/2}$ | 118.67[B] | 118.68[f] | 103.32 | 103.31[f] | 90.10 | 90.05[d] | | 78.56[f] | 68.70[f] | |
| $^4S_{3/2} - ^4P_{3/2}$ | 121.83 | 121.85[f] | 106.06 | 106.05[f] | 92.16 | 92.18[d] | | 80.08[d] | 69.51[f] | |
| $^4S_{3/2} - ^4P_{5/2}$ | 132.88[B] | 132.84[f] | 117.93[B] | 117.92[f] | 104.57 | 104.54[d] | | 92.62[d] | 81.60[f] | |

O I

| | Fe XIX | | Ni XXI | | Zn XXIII | | Ge XXV | | Se XXVII | | Mo XXXV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $2s^2 2p^4 - 2s2p^5$ | | | | | | | | | | | | |
| $^1D_2 - ^1P_1$ | 91.01 | 91.01[a] | 81.73 | 81.70[a] | | 73.59[a] | | 66.38[a] | | 59.88[a] | | 39.16[a] |
| $^3P_2 - ^3P_1$ | 101.56 | 101.56[a] | 88.83 | 88.82[a] | 78.00 | 77.95[a] | | 68.61[a] | | 60.58[a] | | 37.73[a] |
| $^3P_1 - ^3P_0$ | 106.30 | 106.32[a] | | 93.93[a] | | 83.22[a] | | 73.88[a] | | 65.67[a] | | 41.17[a] |
| $^3P_2 - ^3P_2$ | 108.36 | 108.36[a] | 95.91[B] | 95.86[a] | 85.07 | 85.02[a] | 75.49[S] | 75.51[a] | 67.1??[S] | 67.12[a] | 41.94[S] | 41.99[a] |
| $^3P_0 - ^3P_1$ | 109.96 | 109.95[a] | 96.83 | 96.80[a] | | 85.29[a] | | 75.21[a] | | 66.41[a] | | 41.04[a] |
| $^3P_1 - ^3P_1$ | 111.70 | 111.70[a] | 100.26 | 100.24[a] | | 90.58[a] | | 82.38[a] | | 75.39[a] | | 55.93[a] |
| $^3P_1 - ^3P_2$ | 119.98 | 119.99[a] | 109.30 | 109.31[a] | 100.30 | 100.28[a] | 92.44 | 92.53[a] | | 85.81[a] | | 65.83[a] |

F I

| | Fe XVIII | | Ni XX | | Zn XXII | | Ge XXIV | | Se XXVI | | Mo XXXIV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $2s^2 2p^5 - 2s2p^6$ | | | | | | | | | | | | |
| $^2P_{3/2} - ^2S_{1/2}$ | 93.92 | 93.93[a] | 83.23 | 83.18[a] | 73.94 | 73.94[a] | 65.93[S] | 65.90[a] | 58.85[S] | 58.84[a] | 37.63[S] | 37.66[a] |
| $^2P_{1/2} - ^2S_{1/2}$ | 103.94 | 103.94[a] | 94.50 | 94.50[a] | 86.59 | 86.54[a] | 79.77 | 79.75[a] | | 73.87[a] | | 56.54[a] |

Na I

| | Fe XVI | | Ni XVIII | | Zn XX | | Ge XXII | | Se XXIV | | Mo XXXII | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3s-3p | | | | | | | | | | | | |
| $^2S_{1/2}$-$^2P_{3/2}$ | 335.40? | 335.40[e] | 292.00 | 291.97[g] | 256.38 | 256.41[h] | 226.48 | 226.51[h] | 201.01 | 201.06[i] | 127.31 | 127.81[j] |
| $^2S_{1/2}$-$^2P_{1/2}$ | | 360.76[e] | 320.52 | 320.54[g] | 288.16 | 288.22[h] | 261.48 | 261.52[h] | 239.12 | 239.16[i] | 176.64 | 176.62[j] |
| 3p-3d | | | | | | | | | | | | |
| $^2P_{1/2}$-$^2D_{3/2}$ | 251.07? | 251.07[e] | 220.43 | 220.43[g] | 195.38 | 195.38[h] | 174.44[B] | 174.40[h] | 156.43 | 156.49[i] | 104.30[B] | 104.27[j] |
| $^2P_{3/2}$-$^2D_{5/2}$ | 262.98? | 262.98[e] | 233.85[B] | 233.76[g] | 210.10 | 210.16[h] | 190.58 | 190.61[h] | 174.08 | 174.12[i] | 126.94 | 126.94[j] |
| $^2P_{3/2}$-$^2D_{3/2}$ | | 265.01[g] | | 236.33[g] | | 213.31[h] | 194.38 | 194.44[h] | 178.54 | 178.63[i] | | 134.61[g] |

Mg I

| | Fe XV | | Ni XVII | | Zn XIX | | Ge XXI | | Se XXIII | | Mo XXXI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $3s^2$-3s3p | | | | | | | | | | | | |
| $^1S_0$-$^1P_1$ | 284.15? | 284.16[e] | 249.18 | 249.18[e] | 220.60 | 220.58[m] | 196.58 | 196.57[k] | 176.04 | 175.92[k] | 115.99 | 115.99[l] |
| $^1S_0$-$^3P_1$ | | 417.26[e] | | 366.82[u] | 326.44 | | 293.24 | 293.4[x] | 265.83 | 265.7[x] | 190.45 | 190.5[x] |
| 3s3p-3s3d | | | | | | | | | | | | |
| $^3P_0$-$^3D_1$ | | 224.75[r] | 197.34 | 197.39[v] | | | | | | | | |
| $^3P_1$-$^3D_2$ | 227.20? | 227.21[e] | | 199.87[v] | 177.52 | 177.66[m] | | 159.14[k] | | 143.36[k] | 96.60 | 96.56[j] |
| $^3P_2$-$^3D_3$ | 233.81? | 233.86[e] | 207.57 | 207.50[v] | 186.27 | 186.35[m] | 168.91 | 168.90[k] | 154.18 | 154.04[k] | | 112.65[l] |
| $^1P_1$-$^1D_2$ | 243.70? | 243.79[e] | 215.91[B] | 215.89[v] | 193.33 | 193.39[m] | 174.71[B] | 174.78[k] | 159.00 | 158.86[k] | | 113.90[l] |
| 3s3p-$3p^2$ | | | | | | | | | | | | |
| $^3P_2$-$^3P_2$ | | | | 266.15[v] | 234.35 | 234.38[m] | | | | | | |

Al I

| | Fe XIV | | Ni XVI | | Zn XVIII | | Ge XX | | Se XXII | | Mo XXX | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $3s^2 3p - 3s^2 3d$ | | | | | | | | | | | | |
| $^2P_{1/2}-^2D_{3/2}$ | 211.32 | 211.32[e] | 185.19 | 185.22[e] | 164.08 | 164.15[m] | 146.53 | 146.52[o] | 131.61 | 131.69[o] | | 86.87[o] |
| $^2P_{3/2}-^2D_{5/2}$ | 219.12 | 219.12[e] | 194.01 | 194.04[n] | 173.96 | 173.99[m] | 157.46 | 157.55[o] | 143.61 | 143.69[o] | 104.30[B] | 104.33[o] |
| $^2P_{3/2}-^2D_{3/2}$ | 220.09 | 220.08[e] | | | 175.50 | 175.52[m] | 159.34[B] | 159.25[o] | 145.82 | 145.80[o] | 105.58 | 105.59[o] |
| $3s^2 3p - 3s 3p^2$ | | | | | | | | | | | | |
| $^2P_{1/2}-^2P_{3/2}$ | 252.19? | 252.20[e] | | 218.39[n] | 190.64 | 190.71[m] | 167.52 | 167.49[o] | 147.70 | 147.62[o] | 92.56 | 92.55[o] |
| $^2P_{1/2}-^2P_{1/2}$ | 257.42? | 257.39[e] | | 223.09[n] | 194.74 | 194.80[m] | | 170.81[o] | 150.40 | 150.33[o] | 91.38 | 91.3[o] |
| $^2P_{3/2}-^2P_{3/2}$ | 264.75? | 264.79[e] | 232.52 | 232.49[n] | 206.16 | 206.24[m] | 184.30 | 184.34[o] | 165.70 | 165.83[o] | | 114.10[o] |
| $^2P_{3/2}-^2P_{1/2}$ | 270.49? | 270.52[e] | 237.88 | 237.87[n] | | 211.03[m] | 188.42[B] | 188.37[o] | | 169.05[o] | 112.17[B] | 112.16[o] |
| $^2P_{1/2}-^2S_{1/2}$ | 274.20? | 274.20[e] | 239.53 | 239.53[n] | 211.60 | 211.60[m] | 188.42[B] | 188.42[o] | 168.90 | 168.90[o] | 112.17[B] | 112.16[o] |
| $^2P_{3/2}-^2S_{1/2}$ | 289.19? | 289.16[e] | | | | | | | | | | |
| $^2P_{1/2}-^2D_{3/2}$ | | | | 288.17[p] | | 249.34[m] | 220.9?? | 220.88[o] | 194.46 | 194.44[o] | 122.40 | 122.40[o] |
| $^2P_{3/2}-^2D_{5/2}$ | | 353.83[e] | | 309.18[p] | | 272.09[m] | 242.73 | 242.8[o] | 217.00 | 216.86[o] | 140.72 | 140.77[o] |

Si I

| | Fe XIII | | Ni XV | | Zn XVII | | Ge XIX | | Se XXI | | Mo XXIX |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3s^2 3p^2 - 3s 3p^3$ | | | | | | | | | | | |
| $^3P_0 - ^3S_1$ | 240.69? | 240.71[e] | | 209.18[n] | | 183.51[m] | | | | | |
| $^3P_1 - ^3S_1$ | 246.21? | 246.21[e] | 215.91[B] | 215.94[n] | | 191.57[m] | | | | | |
| $^3P_2 - ^3S_1$ | 252.00? | 251.95[e] | 221.98 | 221.93[n] | 197.62 | 197.58[m] | | | | | |
| $3s^2 3p^2 - 3s^2 3p 3d$ | | | | | | | | | | | |
| $^1D_2 - ^1F_3$ | 196.53 | 196.53[e] | 173.72 | 173.73[n] | 155.71 | 155.75[m] | 141.10 | | 129.02[B] | | |
| $^3P_1 - ^3D_2$ | 200.03 | 200.02[e] | | 174.99[r] | | 155.04[m] | | | | | |
| $^3P_1 - ^3D_1$ | 201.16 | 201.12[e] | | 176.10[n] | | 162.21[m] | | | | | |
| $^3P_0 - ^3P_1$ | 202.04 | 202.04[e] | 176.69 | 176.69[e] | | 150.85[m] | | | | | |
| $^3P_1 - ^3P_0$ | 202.40? | 202.42[e] | | | | | | | | | |
| $^3P_2 - ^3D_2$ | | | 178.89 | 178.87[n] | | 158.98[m] | | | | | |
| $^3P_2 - ^3D_3$ | 203.80 | 203.83[e] | 179.25 | 179.27[e] | 159.43 | 159.47[m] | 142.97 | 143.04[k] | 129.02[B] | 129.5[s] | |
| $^1S_0 - ^1P_1$ | 208.68 | 208.68[e] | | | | 165.03[m] | | | | | |
| $^3P_1 - ^3P_2$ | 209.62 | 209.62[e] | | 184.89[n] | | | | | | | |
| $^3P_2 - ^3P_2$ | 213.78 | 213.77[e] | 189.25[B] | 189.21[n] | | 169.69[m] | | | | | |
| $^1D_2 - ^1D_2$ | 221.82? | 221.82[e] | 195.51 | 195.52[n] | | | | | | | |

P I

| | Fe XII | | Ni XIV | | Zn XVI | | Ge XVIII | | Se XX | | Mo XXVIII |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3s^2 3p^3 - 3s^2 3p^2 (^3P) 3d$ | | | | | | | | | | | |
| $^2D_{3/2} - ^2F_{5/2}$ | 186.87[B] | 186.86[q] | | | | | | | | | |
| $^2D_{5/2} - ^2F_{7/2}$ | 186.87[B] | 186.88[e] | 164.15 | 164.13[e] | 146.14 | 146.23[m] | 131.42 | 131.3[s] | 119.03 | 119.7[s] | |
| $^2P_{1/2} - ^2D_{3/2}$ | 188.23[B] | 188.22[e] | | 164.80[n] | | | | | | | |
| $^2P_{3/2} - ^2D_{5/2}$ | 191.02 | 191.05[e] | | 168.37[n] | | | | | | | |
| $^4S_{3/2} - ^4P_{1/2}$ | 192.39 | 192.39[e] | | 168.12[e] | | | | | | | |
| $^4S_{3/2} - ^4P_{3/2}$ | 193.51 | 193.51[e] | | 169.68[e] | | | | | | | |
| $^4S_{3/2} - ^4P_{5/2}$ | 195.11 | 195.12[e] | 171.36 | 171.36[e] | 152.33 | 152.40[m] | 136.71 | 136.7[s] | 123.34 | 123.3[s] | |
| $3s^2 3p^3 - 3s^2 3p^2 (^1D) 3d$ | | | | | | | | | | | |
| $^2P_{1/2} - ^2P_{3/2}$ | 198.55 | 198.56[e] | | | | | | | | | |

S I

| | Fe XI | | Ni XIII | | Zn XV | | Ge XVII | | Se XIX | | Mo XXVII |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3p^4-3p^3(^4S)3d$ | | | | | | | | | | | |
| $^3P_2-^3D_2$ | 178.06 | 178.06[e] | | 155.12[n] | | 137.06[m] | | | | | |
| $^3P_2-^3D_3$ | 180.36[B] | 180.40[e] | 157.66[B] | 157.73[r] | 140.00[B] | 139.85[m] | 124.99 | 125.0[s] | 112.39 | 112.5[s] | |
| $^3P_1-^3D_2$ | 182.11[B] | 182.17[e] | 159.96[B] | 159.97[n] | | 142.74[m] | | | | | |
| $3p^4-3p^3(^2D)3d$ | | | | | | | | | | | |
| $^1D_2-^1F_3$ | 179.74 | 179.76[e] | 157.66[B] | 157.55[n] | 140.00[B] | 140.43[m] | 126.48 | 126.4[s] | 113.93 | 114.0[s] | |
| $^1D_2-^1D_2$ | 184.78 | 184.79[e] | | 161.56[n] | | 143.68[m] | | | | | |
| $^3P_2-^3P_2$ | 188.23[B] | 188.22[e] | 164.15[B] | 164.15[n] | 142.15 | 142.18[m] | | | | | |
| $^3P_1-^3P_1$ | 189.06 | 189.12[e] | | | | | | | | | |
| $^3P_1-^3S_1$ | 192.01[B] | 192.02[q] | | | | | | | | | |
| $^3P_1-^3P_2$ | 192.82? | 192.81[e] | | | | | | | | | |
| $3p^4-3p^3(^2P)3d$ | | | | | | | | | | | |
| $^3P_2-^3P_2$ | | | | | 151.72 | 151.77[m] | | | | | |
| $^1D_2-^1F_3$ | | | | | 157.51 | 157.52[m] | | | | | |

Ar I

| | Fe IX | | Ni XI | | Zn XIII | | Ge XV | | Se XVII | | Mo XXV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3p^6$-$3p^5 3d$ | | | | | | | | | | | |
| $^1S_0$-$^1P_1$ | 171.06 | 171.07[e] | 148.30 | 148.37[r] | 130.99 | 131.06[m] | 117.20 | 117.25[k] | 105.84 | 105.9[s] | 74.31 |
| $^1S_0$-$^3D_1$ | 217.10 | 217.10[e] | | 186.98[w] | | | | | | | |
| $^1S_0$-$^3P_1$ | 244.89? | 244.91[e] | 211.51 | 211.44[w] | | | | | | | |

K I

| | Fe VIII | | Ni X | | Zn XII | | Ge XIV | | Se XVI | | Mo XXIV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3p^6 3d$-$3p^5 3d^2(^3F)$ | | | | | | | | | | | |
| $^2D_{3/2}$-$^2D_{3/2}$ | 167.47 | 167.49[e] | 144.23 | 144.21[r] | 126.65 | 126.74[m] | 112.90 | 112.96[k] | 101.70 | 102.2[s] | |
| $^2D_{5/2}$-$^2D_{5/2}$ | 168.16? | 168.17[e] | | 144.99[r] | 127.53 | 127.62[m] | 113.85 | 113.93[k] | 102.71 | 102.6[s] | |
| $^2D_{5/2}$-$^2F_{7/2}$ | | 185.22[e] | 158.35 | 158.37[t] | 138.36 | 138.42[m] | | 122.82[k] | | 109.9[s] | |
| $^2D_{3/2}$-$^2F_{5/2}$ | | 186.61[e] | | 159.97[t] | 140.00[B] | 140.12[m] | | | | | |
| $3p^6 3d$-$3p^5 3d^2(^3P)$ | | | | | | | | | | | |
| $^2D_{5/2}$-$^2P_{3/2}$ | | 168.55[e] | | 145.78[t] | 128.03 | 128.01[m] | | | | | |
| $^2D_{3/2}$-$^2P_{1/2}$ | | 168.93[e] | | 146.12[t] | | 128.34[m] | | | | | |
| $3p^6 3d$-$3p^5 3d^2(^1D)$ | | | | | | | | | | | |
| $^2D_{5/2}$-$^2F_{7/2}$ | 224.34? | 224.35[e] | | | | | | | | | |

[a]B. Edlen, Ref. 25

[b]B. Edlen, Ref. 26

[c]B. Edlen, Ref. 28

[d]Behring et al., Ref. 20

[e]Behring et al., Ref. 11

[f]B. Edlen, Ref. 27

[g]B. Edlen, Ref. 24

[h]Kononov et al., Ref. 14

[i]Brown et al., Ref. 21

[j]Burkhalter et al., Ref. 12

[k]Fawcett and Hayes, Ref. 10

[l]Reader, Ref. 18

[m]Sugar and Kaufman, Ref. 23

[n]Fawcett and Hayes, Ref. 7

[o]Hinnov et al., Ref. 22

[p]Fawcett and Hatter, Ref. 15

[q]Bromage et al., Ref. 13

[r]Behring et al., Ref. 6

[s]stratton et al., Ref. 17

[t]Goldsmith and Fraenkel, Ref. 5

Cl I

| | Fe X | | Ni XII | | Zn XIV | | Ge XVI | | Se XVIII | | Mo XXVI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $3p^5-3p^4(^3P)3d$ | | | | | | | | | | | |
| $^2P_{3/2}-^2D_{5/2}$ | 174.53 | 174.53[e] | 152.11 | 152.15[r] | 134.74 | 134.80[m] | 120.75 | 120.9[s] | 109.15 | 109.1[s] | |
| $^2P_{1/2}-^2D_{3/2}$ | 175.27 | 175.26[e] | | 153.17[t] | 135.53 | 135.59[m] | | 121.8[s] | | 109.9[s] | |
| $^2P_{3/2}-^2P_{3/2}$ | 177.24 | 177.24[e] | 154.14 | 154.18[r] | 136.24 | 136.31[m] | 121.77 | | 109.96 | | |
| $^2P_{1/2}-^2P_{1/2}$ | 180.36[B] | 180.41[r] | | 157.80[t] | | 140.27[m] | | | | | |
| $3p^5-3p^4(^1D)3d$ | | | | | | | | | | | |
| $^2P_{3/2}-^2S_{1/2}$ | 184.52 | 184.54[e] | | 160.56[n] | | 138.18[m] | | | | | |
| $^2P_{1/2}-^2S_{1/2}$ | 189.99 | 190.04[e] | | 166.88[n] | 145.04 | 145.03[m] | | | | | |
| $^2P_{3/2}-^2D_{5/2}$ | 226.36? | 226.33[r] | | | | | | | | | |
| $^2P_{3/2}-^2D_{3/2}$ | 230.08? | 230.13[r] | | | | | | | | | |
| $^2P_{3/2}-^2P_{1/2}$ | | | | | 174.72 | 174.70[m] | | | | | |
| $^2P_{1/2}-^2P_{1/2}$ | | | | | | 185.78[m] | | | | | |
| $3p^5-3p^4(^3P)3d$ | | | | | | | | | | | |
| $^2P_{3/2}-^4D_{3/2}$ | 256.36? | 256.37[r] | | | | | | | | | |
| $3p^5-3p^4(^1S)3d$ | | | | | | | | | | | |
| $^2P_{1/2}-^2D_{3/2}$ | | | | | 153.71 | 153.69[m] | | | | | |

[u]Peacock et al., Ref. 19

[v]Fawcett et al., Ref. 8

[w]Svensson et al., Ref. 9

[x]Finkenthal et al., Ref. 16

[B]Blend.

[S]Observed in second order.